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SYSTEMS ENGINEERING CAPSTONE PROJECT REPORT

SYSTEMS ENGINEERING OF UNMANNED DOD SYSTEMS: FOLLOWING THE JOINT CAPABILITIES INTEGRATION AND DEVELOPMENT SYSTEM / DEFENSE ACQUISITION SYSTEM PROCESS TO DEVELOP AN UNMANNED GROUND VEHICLE SYSTEM

by

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SYSTEMS ENGINEERING OF UNMANNED DOD SYSTEMS: FOLLOWING THE JOINT CAPABILITIES INTEGRATION AND DEVELOPMENT SYSTEM / DEFENSE ACQUISITION SYSTEM PROCESS TO DEVELOP AN UNMANNED GROUND VEHICLE SYSTEM

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Submitted in partial fulfillment of the
requirements for the degrees of

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ABSTRACT

The objective of this capstone project was to build a simulated system using the Joint Capabilities Integration and Development System/Defense Acquisition System (JCIDS/DAS) process to gain insight into JCIDS/DAS as it relates to unmanned robotics systems. JCIDS and DAS are the Department of Defense’s procedures and guidelines for acquiring military programs. Using JCIDS/DAS and system engineering (SE) methodology, the team developed a radiological clearance system (RCS) and an unmanned ground vehicle (UGV) using LEGO MINSTORMS. The UGV was named the Threat Exposure and Clearing Hardware Manipulated Autonomously or Networked (TECHMAN). The team researched UGVs, software platforms and the JCIDS /DAS regulations to tailor an SE approach in designing and building the TECHMAN robot, starting with the mission needs and requirements followed by system architecture development. The team tested and evaluated two TECHMAN systems. One system was teleoperated and the other was autonomous. The team compared the test results and other system attributes of the two platforms. The knowledge gained from the project results was used to provide insight into the JCIDS/DAS process with regard to procurement of robotics systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACV	Autonomous Clearance Vehicle
AOA	analysis of alternatives
APA	additional performance attribute
API	application programming interface
CBA	capabilities based assessment
CBRNE	chemical, biological, radiological and nuclear, explosive
CDD	capability development document
COIC	critical operational issues and concerns
CONOPS	concepts of operations
COTS	commercial-off-the-shelf
DAS	Defense Acquisition System
DOD	Department of Defense
DOTMLPF	doctrine, organization, training, materiel, leadership & education, personnel, and facilities
DRM	design reference mission
DT	developmental testing
DT&E	developmental test and evaluation
FFBD	functional flow block diagram
EFF	essential function failure
EMD	engineering manufacturing and development
EMMI	energy, matter, material wealth, information
ESS	effectiveness, suitability, survivability
FNA	functional needs analysis
FOV	family of vehicles
HFE	human factors engineering
ICD	initial capabilities document
IDE	integrated development environment
IED	improvised explosive device
IPR	interim progress report

IPT	integrated product team
ISR	intelligence, surveillance, and reconnaissance
JCIDS	Joint Capabilities Integration and Development System
KPP	key performance parameter
KSA	key system attribute
LCC	life-cycle cost
LDD	LEGO Digital Designer
LRIP	low rate initial production
MDA	Milestone Decision Authority
MDAP	major defense acquisition programs
MDARS	Mobile Detection Assessment Response System
ME	mechanical engineer
MMH/OH	man maintenance hour / operating hour
MS	milestone
MSA	material solution analysis
MSES	Masters of Science In Engineering Systems
MSSE	Masters of Science In Systems Engineering
MTRS	manned transportable robotics system
MOE	measure of effectiveness
MOP	measure of performance
NPS	Naval Postgraduate School
NSCT	non-standard clearing test
OCO	overseas contingency operations
OCU	operator control unit
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
OND	Operation New Dawn
OODA	observe, orient, decide, and act
OT	operational testing
OT&E	operational test and evaluation
OUSD (AT&L)	Office of the Under Secretary of Defense for Acquisition, Technology and Logistics

OV-1	operational view
P&D	production and deployment
PDR	production design review
PM	program manager
POR	program of record
R&D	research and development
RAM	reliability, availability, and maintainability
RCS	Radiological Clearance System
REF	Rapid Equipping Force
RFP	request for proposal
RS JPO	Robotic Systems Joint Project Office
SD	software developer
SE	systems engineering
SEMP	system engineering management plan
SNCT	standard nominal clearing test
SV-4	system functional description
TCP/IP	transmission control protocol/Internet protocol
T&E	test and evaluation
TCV	Teleoperated Clearance Vehicle
TECHMAN	Threat Exposure and Clearing Hardware Manipulated Autonomously or Networked
TMRR	technology maturity and risk reduction
TTP	techniques, tactics, and procedures
TW	technical writer
UGV	unmanned ground vehicle
UMS	unmanned systems
WBS	work breakdown structure

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EXECUTIVE SUMMARY

Unmanned systems (UMSs) have become an integral part of U.S. military operations and have proven themselves effective force multipliers by providing the warfighter with enhanced capabilities while reducing their exposure to potentially dangerous environments. By the end of 2010, the DOD had deployed nearly 8,000 unmanned ground vehicles (UGVs) (Office of the Under Secretary of Defense for Acquisition, Technology and Logistics et al. 2006, 5). By the end of 2011, UGVs had participated in over 125,000 missions and defeated over 11,000 improvised explosive devices (Department of Defense 2011, 23).

At present, most UGV systems in the U.S. military inventory were fielded under various rapid fielding initiatives in lieu of the full Joint Capabilities Integration Development System (JCIDS) process and Defense Acquisition System (DAS). Although there may be many reasons for this, the team's research indicated that the most prominent reason is the need to rapidly deploy new capability to warfighters due to the operational demands of Operation Iraqi Freedom (OIF) / Operation New Dawn (OND), and Operation Enduring Freedom (OEF). However, a secondary reason why the JCIDS/DAS process is avoided is the added cost, time, and requirements it imposes on the acquisition effort. Maintainability, usability, and making sure that the system provides a new capability rather than duplicating an existing one are all examined by JCIDS/DAS, but can be omitted under rapid fielding. Following the JCIDS/DAS process forces system designers to plan for these additional design factors that some rapid fielding efforts have omitted. Thus, there is a tradeoff between the short-term gains of rapid fielding and long-term design robustness gains that JCIDS/DAS provides.

Project TECHMAN is a research project of the difficulties and benefits encountered by UGV systems as they move through the JCIDS/DAS in lieu of using a rapid fielding initiative. To test this, the TECHMAN team created two Remote Clearance Vehicles under simulated JCIDS/DAS conditions. The first, the Teleoperated Clearance Vehicle (TCV), performs clearance operations while being controlled remotely by an

operator. The other, the Autonomous Clearance Vehicle (ACV), performs clearance operations autonomously. Both vehicles enter a target area to pick up small vials representing hazardous targets, and then they return the vials for safe disposal by an operator.

The team followed a simulated version of the JCIDS/DAS process by creating work items such as a capability needs assessment, analysis of alternatives, requirements analysis, system hardware and software architectures, system design, and a test and evaluation plan. The team also met at Aberdeen Proving Ground, Maryland, to carry out formal system tests on the two TECHMAN prototypes.

The TECHMAN prototypes successfully completed testing. The TCV was found to be more accurate at clearing vials; however, the TCV required the operator's full attention. The TCV also required the operator have line of sight of the clearing area. The ACV was not as accurate at clearing the vials as the TCV but still managed to eventually clear all of the vials. The ACV mission time was longer than the TCV but the ACV did not require the full attention of the operator.

The project showed the validity of the JCIDS/DAS process throughout the design and build of the TECHMAN systems. If the project continued, the JCIDS/DAS process would help the team mature the design and correct the issues found during the evaluation and ensure the system to be fielded meets the user need while being reliable, maintainable, and supportable. These artifacts are discussed in detail in this report.

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We would also like to thank our family members for their dedication and support. Time we spent in our coursework was time away from them. We appreciate their patience, understanding, sacrifice and diligence in assuming our responsibilities during our absence. They truly made our success possible.

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I. INTRODUCTION AND BACKGROUND

A. INTRODUCTION

This capstone report has been developed by a team of students at the Naval Postgraduate School (NPS) in the Master of Science in Systems Engineering (MSSE) and Master of Science in Engineering Systems (MSES) distance learning cohort 311-142O. The team used the Joint Capabilities Integration and Development System (JCIDS), the Defense Acquisition System (DAS), and a System Engineering (SE) approach to develop a Radiological Clearance System (RCS) and build an unmanned ground vehicle (UGV) using the LEGO MINSTORMS EV3 platform. The team named the UGV the Threat Exposure and Clearing Hardware Manipulated Autonomously or Networked (TECHMAN). Although the RCS only simulates a real military system, its development during this project followed the processes contained in the JCIDS and DAS. Over the nine months of the project the team researched UGVs, JCIDS/DAS, and software development for the TECHMAN. Based on the JCIDS and DAS regulations, the team tailored an SE process to develop and built the TECHMAN robot followed by test and evaluation. The team evaluated the test data and system attributes to determine each system's effectiveness.

B. BACKGROUND

Throughout the past decade, unmanned systems (UMSs) have become an integral part of United States military operations. UMSs have proven to be effective force multipliers, providing the warfighter with enhanced capabilities while reducing their exposure to potentially dangerous environments. The majority of currently fielded UMSs are in response to capability gaps identified by the warfighter's need for heightened intelligence, surveillance, and reconnaissance (ISR) as well as chemical, biological, radiological and nuclear, explosive (CBRNE) threats (Department of Defense 2011, 22).

The ongoing operations of the Department of Defense (DOD) in Iraq and Afghanistan have led to the deployment of thousands of UMSs. By the end of 2006, the DOD had deployed nearly 4,000 UGVs (Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (OUSD(AT&L)) et al. 2006, 5) with numbers reaching approximately 8,000 by the end of 2010. At this point, UGVs alone had participated in over 125,000 missions and defeating over 11,000 improvised explosive devices (IEDs) (Department of Defense 2011, 23). UMSs have become a tremendous asset for modern U.S. forces, extending areas of operation, and saving military lives by removing the warfighter from dangerous situations.

According to the Unmanned Systems Integrated Roadmap, UMSs "are a powered physical system with (optionally) no human operator aboard the principal platform, which can act remotely to accomplish assigned tasks. UGS may be mobile or stationary, can be smart learning and self-adaptive, and include all associated supporting components such as operator control units (OCU)" (Department of Defense 2013, 6). When operating in hazardous, unfamiliar environments, it is preferable for warfighters to investigate potentially dangerous objects via some remote means. The utilization of autonomous or teleoperated UMSs enables the development of techniques, tactics and procedures (TTPs) to significantly reduce the potential of injury or casualty to service members from hazardous threats.

Today, modern U.S. forces have been able to reduce manning requirements, extend operational areas, and save military lives by adding UMSs to the force structure. Recent advancements in UMSs have further subdivided by their ability to accomplish assigned tasks with or without continuous input from their operators, referring to the level of autonomy the said system is capable. The majority of UGVs currently fielded by the DOD, such as the man transportable robotics system (MTRS), Dragon Runner 10, and MarcBot IV-N, are only capable of being directly teleoperated by a human. There are a number of limited UGVs capable of semi-autonomous operation, such as the Mobile Detection Assessment Response System (MDARS). However, this limited autonomy only allows for completing relatively simplistic or repetitive actions (OUSD(AT&L)). Enabling UMSs with greater levels of autonomy is currently the subject of extensive

research and development by the DOD and its industry partners (Robotic Systems Joint Project Office (RS JPO) 2011, 22).

Achieving improved system, sensor, and analytical autonomy of UMSs would allow for advanced teaming of manned and unmanned assets while simultaneously reducing the manpower requirements for operating UMSs. This would lead to decreasing key budgetary cost drivers as well as reducing or eliminating the exposure of human lives to dangerous situations, both of which are important goals for the DOD (Department of Defense 2013, 29). As new generations of UMSs are developed, it is likely they will have the ability of executing operational tasks superior to what humans are capable of. With the advancement of unmanned technology, hazardous tasks will be able to be performed remotely with limited to no human interaction. Additionally, the capabilities of UMSs will expand as improvements are made to sensor technologies, software algorithms, and artificial intelligence (Department of Defense 2013, 15).

Although the deployment of UMSs has led to significant success in protecting service members from new and rapidly evolving threats in combat zones, the majority of these systems were acquired as commercial-off-the-shelf (COTS) systems using rapid acquisition methods eschewing the traditional DOD acquisition framework. The proliferation of IEDs resulted in Joint Urgent Operational Needs Statements (JUONSs) and Operational Needs States (ONSs) requesting additional solutions to combat the enemy's use of unanticipated weapons and tactics (Baca 2012, 3). DOD organizations such as the Army's Rapid Equipping Force (REF) were able to mitigate many of these new capability gaps through the deployment of UMSs funded by overseas contingency operations (OCO) funds (Baca 2012, 4).

The urgent wartime need for these systems prompted by the JUONSs/ONSs, the rapid fielding of these systems allowed the DOD to combat the immediate threat, however these acquisitions did not follow the JCIDS/DAS process necessary for ensuring a viable long-term solution. By circumventing the JCIDS/DAS process, a functional needs analysis (FNA) was not conducted nor was proper consideration given to the doctrine, organization, training, materiel, leadership and education, personnel, and

facilities (DOTMLPF) aspects of these systems to ensure long term sustainability (Baca 2012, 4). Additionally, the rapid fielding of these systems without the coordination of established program of records (POR) resulted in a fractured state causing duplications of effort, integration challenges from proprietary designs, and extreme costs in labor, time, and OCO funding (The Industrial College of the Armed Forces 2011, 14). The resultant systems were too immature in terms of reliability and supportability, relying heavily on contractor logistics support, which is unsustainable (Department of Defense 2013, 93).

For sustained operations, a more systematic approach is required that looks at all the factors involved in developing, supporting, and maintaining UMSs through the complete product life-cycle. Systems developers must establish cost effective, long-term life-cycle sustainment strategies capable of fulfilling warfighter requirements (Department of Defense 2013, 93). Therefore, the team applied an SE approach to the development of two UMSs within the JCIDS/DAS process to see where improvements can be achieved in the process and the systems themselves.

C. LITERATURE REVIEW

The capstone team performed a literature review with the intent of establishing a foundation of knowledge based on existing publications and research focused on the DOD's research, development, acquisition, and fielding of UMSs.

The Unmanned Systems Integrated Roadmap, a biennial publication of the DOD, is intended to communicate the unified "vision and strategy for the continued development, production, test, training, operation, and sustainment of unmanned systems technology across the DOD" (Department of Defense 2013, v). These reports outline the current state of ongoing DOD efforts related to air, ground, and maritime UMSs. The TECHMAN team used this report series to form a baseline understanding of current and planned UMS applications within the DOD.

The Unmanned Ground Systems Roadmap is published by the Robotic Systems Joint Project Office (RS JPO) to establish their short and long-term goals and strategies relating to the development and acquisition of unmanned ground systems (Robotic

Systems Joint Project Office 2011, 5). This report provided the team with detailed information on specific COTS and POR UGVs currently fielded by the DOD.

COL Glenn Baca conducted a research project for the United States Army War College titled *An Analysis of U.S. Army Unmanned Ground Vehicle Strategy*. Baca investigated the current DOD and emerging Army strategies related to UGVs (Baca 2012). This report provided the team with initial awareness of the negative long-term effects associated with bypassing the JCIDS/DAS process in favor of the rapid fielding process to supply forces with UMSs.

The Defense Science Board published the Task Force Report: The Role of Autonomy in DOD Systems. This report contained the results of their study on the operational benefits, capability, technical issues, and acquisition issues of autonomy-related plans of the DOD (Defense Science Board 2012, 5). This report provided the team with insight into the current challenges and technological limitations faced by the DOD when developing autonomous systems.

The team also utilized the paper "Destruction and Creation" by Air Force COL John Boyd. In this seminal paper, Boyd details the observe, orient, decide, act (OODA) strategy used by decision makers, also known as the OODA Loop (Boyd 1976). The TECHMAN ACV's autonomous decision making features were designed to model Boyd's OODA Loop.

D. PROBLEM STATEMENT

The DOD has received increased funding and support for the development of UMSs due to their usefulness in the field, however, the success rate for meeting cost, schedule, performance, and supportability objectives for development and fielding UMSs in the Department of Defense has, in general, been low. Although the importance of UMSs will continue to grow, the success of UMS acquisition projects continues to be a problem. The DOD needs to identify and understand the reasons behind the limited efficacy of the current JCIDS/DAS in terms of UMS development as well as establish a

strategy to address these shortcomings. A high level graphic of the JCIDS/DAS process is shown in Figure 1.

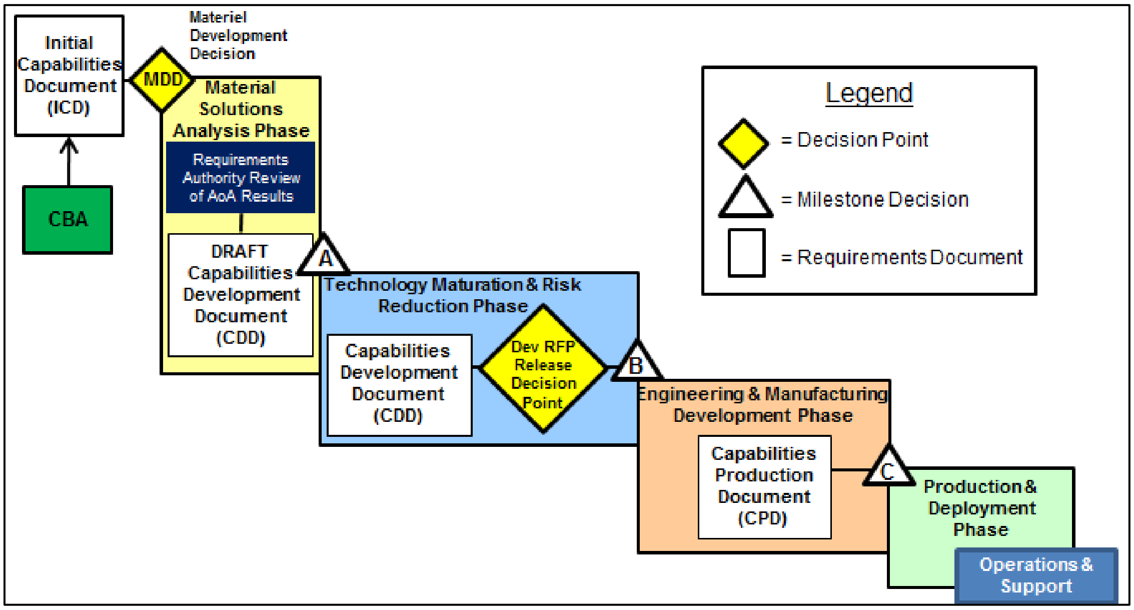


Figure 1. High Level View of JCIDS (from CJCSI 2015)

There are various types of fielded UMSs that have duplicating or overlapping capabilities. Due to the rapid need for these systems to meet present wartime demands, the majority of these systems have been developed without the benefits of going through the traditional JCIDS/DAS process. The rapid fielding process lacks many of the aspects of the JCIDS/DAS process. The primary focus during development has been meeting mission operational objectives. This rapid development process has been performed with weak consideration of many factors, such as: affordability, supportability, life-cycle support, reliability, availability, maintainability, interoperability, and logistics. This has caused long term problems related to cost, performance, and supportability throughout the life-cycle of UMSs. While this approach to UMS development may be appropriate for wartime contingency operations, it has proven to be inadequate for systems that are expected to perform for periods of long-term sustained operations.

The solution may involve finding a balance in merging the rapid fielding process with the JCIDS/DAS process. Whatever the solution may be, as long as acquirers feel that the life-cycle planning required by JCIDS/DAS regulations are incompatible with rapid acquisition, support problems will continue.

E. PROJECT OBJECTIVES

There were three objectives for this project. The main objective was to improve the team members' understanding of the SE process by developing an actual hands-on, end-to-end system using the SE process as taught by NPS. The second objective was for the team to better understand what is required to design and develop teleoperated and autonomous robotic systems within the context of the JCIDS/DAS process. The team was specifically interested in how using the JCIDS/DAS process related to cost, schedule, performance, and supportability of UGVs and a comparison of the two systems. The third objective was to support development of NPS CRUSER-supported robotic and unmanned systems graduate teaching material.

F. RESEARCH QUESTIONS

This research project examined the use of LEGO MINSTORMS Robots to simulate the remote removal of hazardous materials. The project was designed to answer the following questions:

1. How well does the JCIDS/DAS process support the acquisition and development of UGVs?

2. What SE approaches, tools, and techniques are critical to successful UGV projects?

3. Given a set of performance and suitability requirements, how easy is it to accurately estimate cost and schedule for UGV projects within the JCIDS/DAS process?

4. How much difference is there in the effort involved with developing teleoperated systems and the effort involved with developing autonomous systems?

5. What are the tradeoffs in sensors and computation for autonomous and teleoperated UGVs?

6. What are the impacts on both acquisition and mission completion when comparing autonomous and teleoperated UGVs?

7. How much of a difference does the choice of software engineering approach make?

G. PROJECT DESCRIPTION AND SCOPE

The team used the scenario that ground forces need a capability to clear terrain of radiological containers. The two TECHMAN variants were developed to meet this capability using LEGO MINSTORMS. Figure 2 shows the operational view (OV-1). The OV-1 illustrates the concept of operations of TECHMAN that is the groundwork for the design reference mission (DRM). The UGV clears vials from the search area by being remotely controlled by the operator or being autonomously controlled by programed logical algorithms in its software. The UGV mission is complete once the vials are removed from the area to be cleared and placed in the corral. Figure 3 is the context diagram for the TECHMAN system. Data and information flows are illustrated between the TECHMAN and various supporting and supported elements of the system.

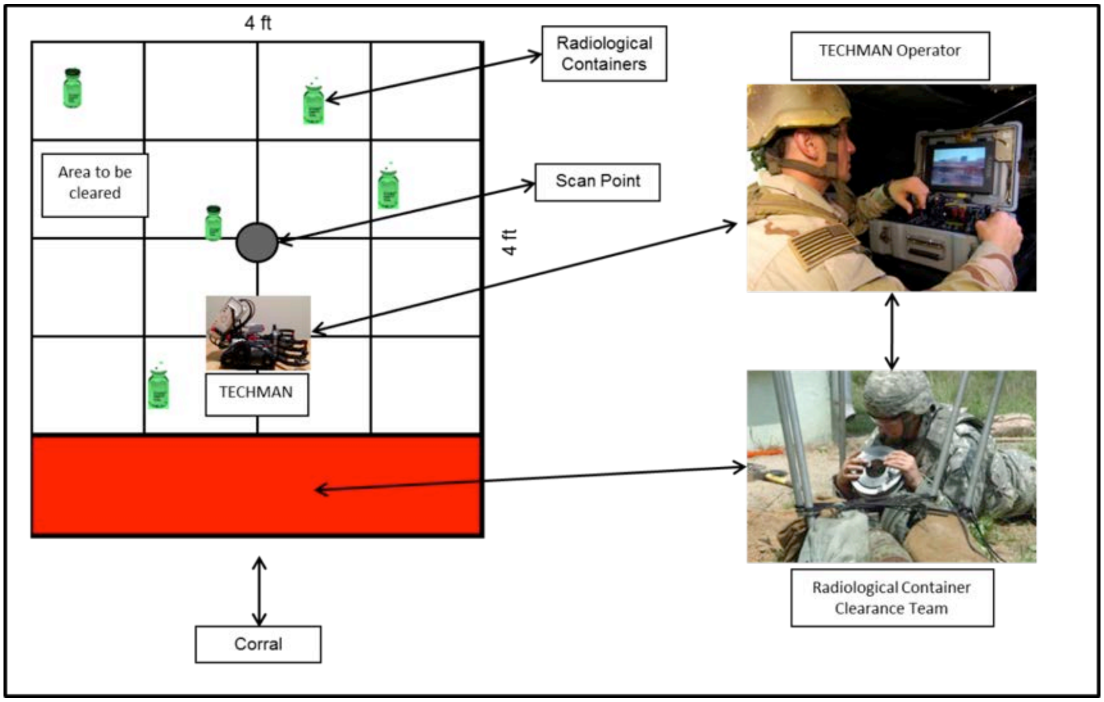


Figure 2. Operational View

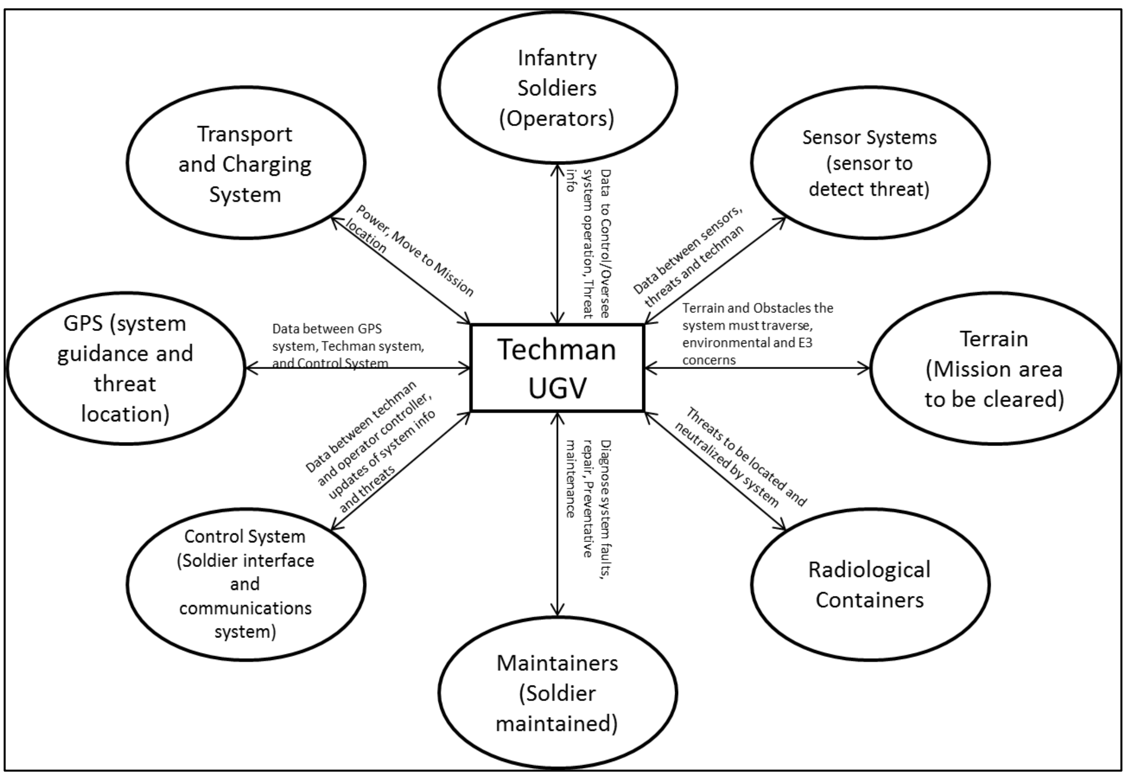


Figure 3. Context Diagram

H. PROJECT ASSUMPTIONS AND CONSTRAINTS

1. Assumptions

The team members assumed the roles of the organizations and personnel involved in an acquisition program up to milestone (MS) B. This drove the team members to take different roles and functions throughout the JCIDS/DAS process which include:

- the user
- program manager
- design engineer
- system builders
- independent test and evaluation team
- logistics managers
- decision authority
- software developers
- technical writers

2. Constraints

The main constraint of the system development was using the LEGO MINDSTORMS EV3 hardware for a material solution. The mechanical strength of the Lego system is inherently weak compared with actual military UGVs. The sensor systems do not have the accuracy or range typically seen with UGVs either. The Lego Mindstorms systems are also limited to the terrain they are able to traverse. To deal with this constraint the team assumed the user would know the technology limitations. The top-level user need is a very realistic need derived from the Unmanned Systems ICD. However, the lower level requirements for how to provide that capability were written with the constraints of Mindstorms in mind. A full system not restricted to Mindstorms limitations might consider a more capable architecture and more aggressive system requirements.

Another constraint for the project was the time allotted to complete all of the JCIDS/DAS deliverables. The time required for a program to reach MS B varies but is normally much more than nine months. To address this, Team TECHMAN only developed deliverables that contained the essence of the JCIDS/DAS process.

The last constraint was that the team members were limited to the skills and abilities of each team member. Although the team included two software developers, neither of them had experience working in either of the two special purpose software environments created specifically for programming Mindstorms devices.

I. APPROACH

1. System Engineering Process

The project team used the full toolbox of systems engineering methods to complete the TECHMAN system. The team identified and implemented configuration management/source control solutions. The team followed the JCIDS/DAS process to MS B in developing the TECHMAN system. The team presented briefings that supported the essence of the JCIDS/DAS documents for milestones A and B. In the JCIDS process, different approaches to achieving the mission are considered in the Analysis of Alternatives. The selection of one of the alternatives occurs at Milestone A. Proposals for systems that selected from the proposed alternatives are solicited and prototypes are refined. Milestone B represents the decision to formally establish the Program Office.

The team used the Vee model of systems engineering, shown in Figure 4, as the road map through the development of the TECHMAN system. The model assisted in:

- development of concept of operations
- defining system requirements
- allocating sub-system functions
- conducting detailed component design
- updating requirements and functions to fit capabilities

- implementing hardware and software solutions
- verification and validation (component, subsystem, and system levels)

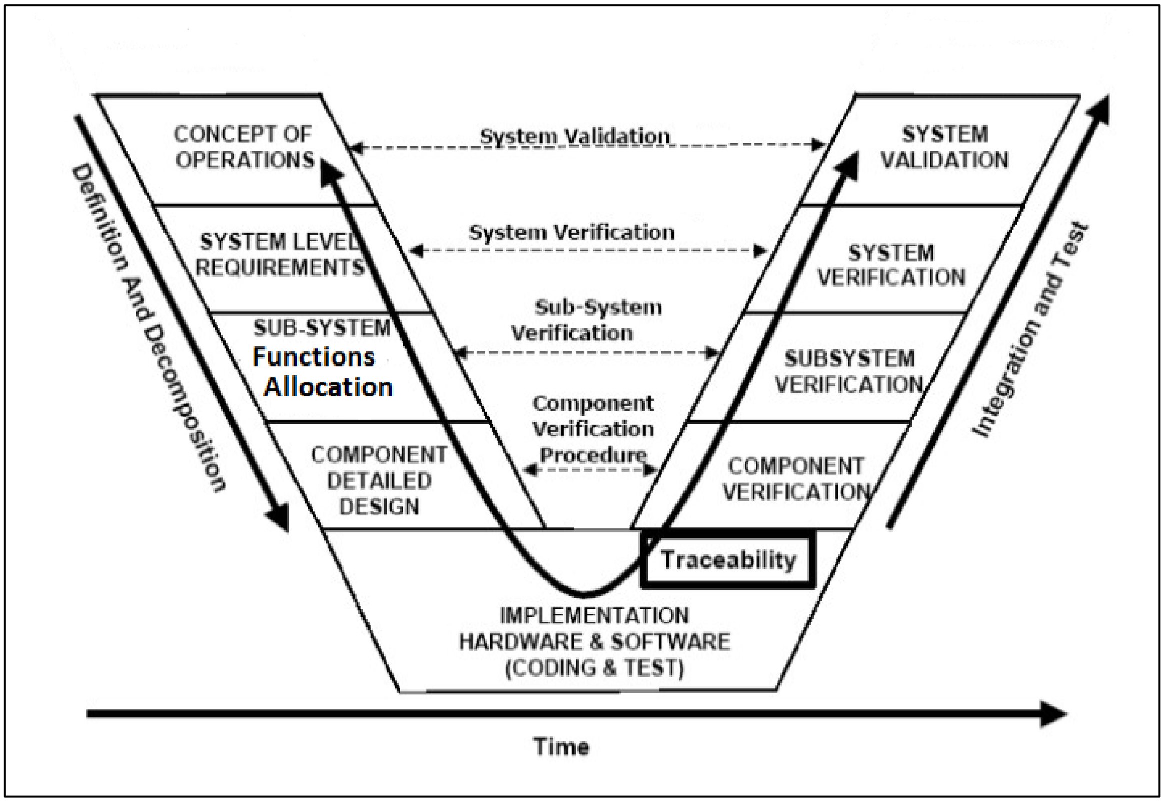


Figure 4. System Engineering Vee (from CSM 2007)

In addition, the team used recognized Software Engineering methodologies in creating the TECHMAN Autonomous Clearance Vehicle (ACV) and TECHMAN Teleoperated Clearance Vehicle (TCV).

a. Initial Research

The team developed the problem statement and reviewed relevant resources to fully understand the problems. The team completed an analysis of alternatives (AOA). The team used the initial capabilities document (ICD) for unmanned systems provided by the NPS capstone advisors. Development of the systems engineering management plan

(SEMP) began in the initial research phase and included initial cost and schedule goals along with risk management.

b. Needs/Requirements Analysis

The ICD for unmanned systems provided the starting point for determining the user capability gap. The team developed a DRM. Operational requirements were developed from the DRM. These requirements were documented in the capability development document (CDD). A draft CDD was created for MS A and the final was completed for MS B. The TECHMAN system requirements were developed from the CDD.

c. System Design

System design and development commenced following finalization of requirements. The system engineering Vee model was used during design and development. The system architecture was developed and tracked throughout the design and build of the system. A life-cycle cost analysis was performed. Documentation was continually updated with the changes in the system design.

d. Test and Evaluation (T&E)

A test and evaluation plan was developed to support system assessment. The plan was structured to ensure that the testing would verify if the requirements were met. Evaluation of test results assessed UGV capability in satisfying system requirements.

e. Milestone B

Once the test and evaluation was complete all documents were updated to support the MS B decision. The CDD was updated with lessons learned during the pre-milestone B research. The SEMP was updated with the final system design and information including cost and risk. The results of the project were briefed covering all of the MS B deliverables and updates to the final system design information including cost and risk.

2. Life-Cycle Engineering

The team used JCIDS/DAS to engineer a life-cycle plan for the TECHMAN prototypes throughout their lives from the initial need to system disposal. Due to the constraints of the stopping at MS B, the team performed many parts of the extended life-cycle (such as training end users and system disposal) as a planning exercise rather than fully carrying out the plan.

a. Conceptual / Preliminary Design

In the conceptual and preliminary design phase the team performed an analysis of requirements followed by the system functional analysis and operational analysis. Once the analysis was completed the team developed engineering models and sub systems prototypes.

b. Detail Design and Development

During the detailed design and development the team designed a base vehicle platform. Software and mission packages were added to the base platform to produce the TECHMAN TCV and TECHMAN ACV. The SE VEE and system architecture were used during the development process to match the system capabilities with the user requirements. The system maintenance plan, training, and logistical support were developed in conjunction with the system design. The final part of the design and development phase was the developmental test and evaluation.

c. Production and/or Construction

The production phase for the TECHMAN was done for planning as the project stopped at MS B. The plan includes production of system components, suppliers, and operational test and evaluation.

d. Utilization and Support

The Production, Utilization and Support phases for the TECHMAN were outside the scope of the project. The project stopped at MS B. The plan for utilization and support includes supporting the system while in operations, change management to account for any engineering changes and phase-out and disposal.

J. ORGANIZATION AND MANAGEMENT

1. Team TECHMAN Organization

The organization of Team TECHMAN is shown in Figure 5. The team consisted of five members with one team lead and two members each on the ACV and TCV sub teams. The two sub teams collaborated on the base design of the system but worked independently while developing the control software.

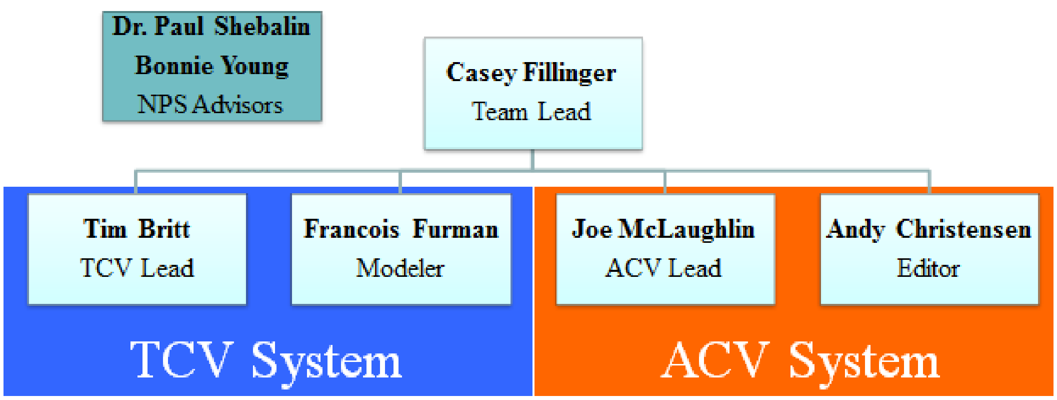


Figure 5. Team TECHMAN Organization

2. Team TECHMAN Management

a. Personnel Management

Except for the T&E session at Aberdeen Proving Ground, the TECHMAN team mostly worked remotely from each other. The team had weekly integrated product team

(IPT) meetings to discuss project progress, cover future work, track and assign work items, and raise issues with other team members. During the IPT meetings, minutes were taken and used as reference notes. The master schedule was used to track progress and ensure tasks and deliverables were completed in a timely manner.

b. Project Management

Progress on the project was tracked using the Earned Value Management (EVM) technique. Under EVM, schedule and cost estimates were developed, then percentage of planned expenditure was used as a proxy to measure the teams progress. Every week, the team reported the number of hours worked on the project. Thus, the Budgeted Cost of Work Scheduled (BCWS) could be compared to the Budgeted Cost of Work Performed (BCWP). When multiplied by an estimated salary and added to the estimated fixed costs (for the cost of the equipment and the cost of performing testing), the team could calculate the Actual Cost of Work Performed (ACWP).

Figure 6 shows a sample EVM chart that the team reported during Week 25. The T&E session at Aberdeen Proving Grounds was conducted during Week 24, which accounts for the spike during that week. Note that the BCWP and BCWS mostly track with each other. The ACWP is lower than the other two because the fixed costs (for the kits and for the testing) were lower than we estimated.

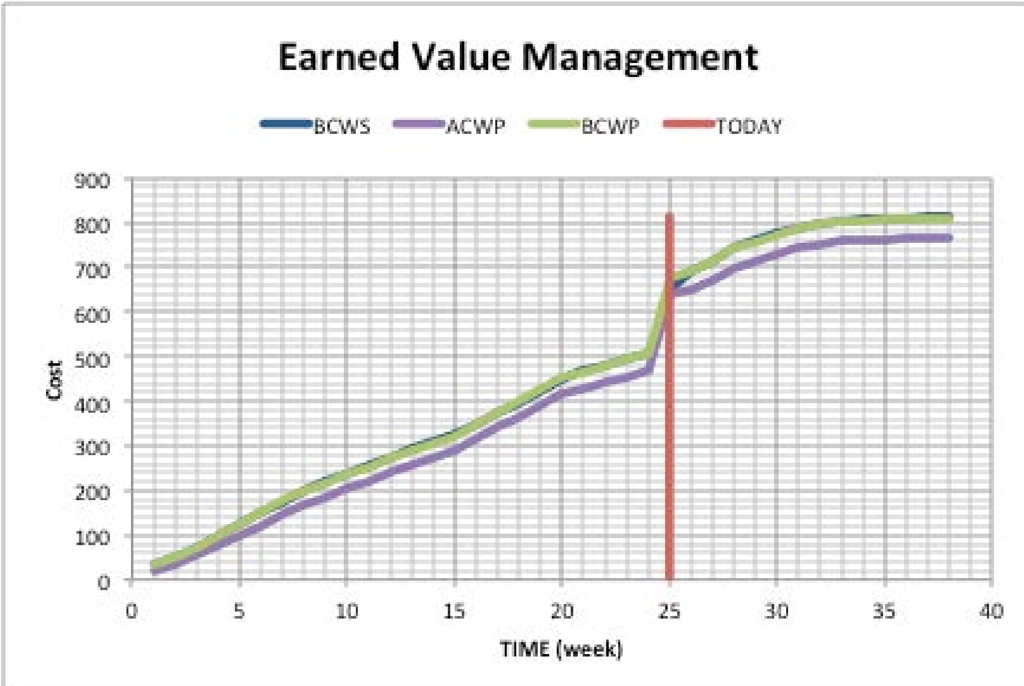


Figure 6. Week 25 EVM Status

Three primary methods were used in project reporting including: weekly meetings, interim progress report (IPR)/Milestone briefings, and the final report. Weekly meeting progress reports were briefed to the NPS advisors during the scheduled class hour. These reports covered completed tasks, upcoming tasks, device progress, and progress on program deliverables. This final report is a consolidated document that covers all elements of the project.

The three IPR/Milestone presentations were briefed to an audience from NPS. The first IPR briefing doubled as the MS A briefing and covered the Analysis of Alternatives, the project plan, and other preliminary information expected at MS A. The second IPR was a formal progress where we discussed the design of the UGVs and showed video of them in operation. We also discussed the T&E plan, because the T&E event was held the following week. The third IPR doubled as the MS B briefing and covered the design and the T&E results. This final IPR was also used as a closeout for the class.

The team used Microsoft OneDrive as the main knowledge management repository. All documentation generated by the TECHMAN team was stored in OneDrive so the entire team could access it and work on it simultaneously. Versioned “releases” of key documents were stored in folders parallel to the living documents. The source code, requirements, and issue tracking was managed through Visual Studio Online source control tool. The source code could be accessed using a locking file access model and the source code can integrate with Eclipse. Code changes, requirements, and issues/bugs were all “linked” to each other.

II. MISSION NEED AND REQUIREMENTS

A. CONCEPT OF OPERATIONS

The system engineer is responsible for the development of the complete system from the statement of the stakeholders needs through system design, development, deployment, and retirement. During this process, the system engineers are involved in the definition of the systems concepts of operations (CONOPS), which spell out how the system will operate to accomplish its mission. The PM will use available resources to accomplish its roles, missions, and functions. The CONOPS is designed to give an overall picture of the operations and describes system characteristics in a fashion to describe how resources will be organized to solve an emerging military problem (CJCSI, 2015).

According to Frittman and Edson, the CONOPS has the potential to add value throughout the acquisition life-cycle but is often underutilized. They point out that, although many in the acquisition community believe the CONOPS is critical to system success, many programs do not develop a CONOPS until after the requirements are written, after the system is developed, or sometimes not at all (Edson and Frittman 2010). The TECHMAN team recognized the importance of developing a high quality CONOPS and chose to adapt the Edison and Frittman CONOPS approach early in the acquisition life cycle and updated it throughout the acquisition life cycle as the system design, anticipated mission profile and system functionality evolved.

The team used methods and skills learned in the MSSE program to develop a Lego Mindstorms-based Radiological Clearance System, which contains an unmanned ground vehicle. The RCS high-level CONOPS was initially developed to feed the simulated JCIDS/DAS process and provide initial input into the capabilities based assessment (CBA). The CONOPS was used to describe the organization, mission, objectives, development, integration, and testing of the system. As the system evolved, the high-level CONOPS matured into a system-level CONOPS. During all phases of the

simulated JCIDS process, the CONOPS was used to communicate user needs and system requirements to system developers, system integrators and system testers to ensure that the RCS met the stakeholder needs and requirements.

The initial high-level CONOPS as presented in this capstone project addresses the JCIDS process from a high-level military needs perspective. It represents the overall capabilities, as requested by the user, to be delivered by the system. The CONOPS was used to communicate user needs, and to map these needs to system requirements and system functions. The CBA was conducted to mature the high-level CONOPS into a system specific CONOPS.

During the JCIDS process, requirements are initially captured in the form of an ICD; however, as the CONOPS evolves throughout the acquisition life-cycle process the requirements documents will change.

The system level CONOPS as captured in the ICD provides a specific description of system requirements, as it existed prior to the material solution analysis (MSA) phase. The system CONOPS continued its evolution and development as the acquisition proceeded through the MSA phase and the technology maturity and risk reduction (TMRR) phase. A full system would proceed through the engineering manufacturing and development (EMD) phase, and the production and deployment (P&D) phases, but they are outside the scope of this project.

1. Primitive High-Level CONOPS

A primitive high-level CONOPS was developed to express the full capability described in the user’s primitive need statement. The system was treated as a “black box” capable of providing the desired capability with few limitations. This primitive CONOPS was used to guide the development of the ICD.

The RCS is a radiological clearance system developed to locate, identify, and remove simulated radiological hazards from an operational area. In the interest of further developing the base of knowledge in this area, Lego Mindstorms prototypes were used to simulate the location, identification, and removal of radiological objects. To permit the

widest distribution possible for the report and associated documentation, the TECHMAN team used inert vials to stand in for hazardous objects. The capstone project also replicated the initial analysis, selection, design, development, deployment, and support of the devices in the SE life-cycle sustainment process.

Lego Mindstorms is a Lego kit consisting of Lego building components, a portable computing module, electric motors, and several different sensors. These components can be assembled and the computing module programmed to perform various mission tasks. During this capstone project, two Lego robots were assembled to locate, identify, and remove inert plastic vials that were marked to simulate radiological hazards. The design teams created an autonomous robot and a teleoperated robot to demonstrate the feasibility of this technology. The two robots were tested and evaluated in a test area to measure and compare their ability to locate, identify, and remove simulated radiological containers.

2. Initial Capabilities Document CONOPS

A capability analysis was conducted to identify existing materiel solutions and non-materiel solutions available to provide a portion of the required capability. The remaining capability requirement was documented in the ICD as a justification for the acquisition of a new materiel system. The CONOPS was refined to remove capabilities provided by existing materiel solutions and non-materiel solutions and included in the ICD to facilitate communication of the capability to be provided by the new system.

3. Material Solution Analysis Phase CONOPS

During the Material Solution Analysis (MSA) phase, the CONOPS provided the basis for analyzing potential concepts for the RCS. The system CONOPS was used to translate capability gaps into system-specific requirements and key performance parameters (KPPs). The system-level CONOPS was used to develop an Analysis of Alternative (AOA) and was the foundation for evaluation of tradeoffs between cost, schedule, and performance during this phase. The system concept solution, risk analysis, and risk mitigation plans were key deliverables that were produced during the MSA

phase. The capabilities of existing systems, as well as other DOTMLPF solutions, were analyzed to see if a suitable effect could be achieved without creating a new system (a non-material solution)(Edson and Frittman 2010) (DODI 2015). For more information on the AOA, see Chapter III.

4. Technology Maturation and Risk Reduction Phase CONOPS

The Technology Maturity and Risk Reduction (TMRR) phase is conducted "to reduce technology, engineering, integration, and life-cycle cost risk to the point that a decision to proceed to EMD could be made" (DODI 2015). The TECHMAN team made design and requirement tradeoffs necessary to ensure a functionally capable RCS was incorporated into the system CONOPS.

In a full system, the TMRR "phase normally includes competitive sources conducting technology maturation and risk reduction events, preliminary design events, to including preliminary design reviews (PDR) prior to source selection for the EMD phase" (DODI 2015). Risk reduction prototypes or competitive prototypes would be included during this phase if they will reduce the EMD risk to an acceptable level (DODI 2015).

Risk reduction prototypes or competitive prototypes can be at the system level or they can focus on the sub-system or component level of the system prior to Milestone B. Competitive prototyping or critical subsystem prototyping of a system is a statutory requirement to be included as part of the Acquisition Strategy for major defense acquisition programs (MDAPs). Technology Readiness Assessments (TRA) Guidance should be used to benchmark technology risk (DODI 2015)

The TECHMAN sub-teams each created a prototype clearance vehicle (the Autonomous Clearance Vehicle and the Teleoperated Clearance Vehicle). At the T&E event, the two prototypes were tested against each other to see which would fulfill the CONOPS more effectively. Technology limitations were identified during the TMRR phase. The CONOPS was updated to match the more mature understanding of the capability to be delivered.

In an acquisition program, the acquisition strategy will direct the TMRR phase, with multiple technology development demonstrations taking place before the customer and program manager (PM) can determine that a chosen solution is technologically feasible, affordable, effective, suitable, and survivable (DODI 2015). The chosen technical solution must demonstrate that it satisfies the systems capability requirements and that the technical risks are acceptable. During the TMRR phase, the PM is required to plan and update the acquisition strategy for Milestone Decision Authority (MDA) approval. The updated acquisition strategy will describe the overarching approach to fulfilling the system capabilities, which will include the programs schedule, cost, performance and business strategy (DODI 2015).

During the TMRR phase of a full project, the PM will make the initial critical life-cycle sustainment decisions for the RCS. These decisions should be initiated early when requirements tradeoff and design decisions are being made (DODI 2015). Finalizing the life-cycle requirements, the PM will decompose them into detailed requirements to support the PDR (DODI 2015). The TECHMAN team performed a limited form of life-cycle planning due to the limited scope of the project.

5. Engineering and Manufacturing Development Phase CONOPS

For an acquisition program at the MS B decision, the MDA provides the authorization to award contracts and enter the EMD phase of the DAS process. MS B is the point at which investment resources are committed to the program and a request for proposals (RFP) is released to the public to submit offers. The system CONOPS is a key portion of this step. If the guidelines discussed in this capstone project are followed, contractors submitting proposals should have a complete and accurate listing of the desired system's operational and functional requirements. Therefore, they should be able to complete proposals to build systems which provide the capability set to meet the system requirements. At MS B, all risks (technology, engineering, integration, life-cycle, manufacturing, development, and cost) should be adequately mitigated to support design production. When an acquisition program is developed in this fashion, the system

CONOPS becomes a key document in accurately developing the program’s cost, schedule, and performance estimates.

The goal of the EMD phase for an acquisition program is to develop, build and test the system in order to verify that all operational requirements have been met in order to support a production and deployment decision. During EMD, all hardware and software designs are completed. System prototypes are built and tested to verify compliance with capability requirements. The PM prepares for production or deployment and establishes the initial product baseline. EMD will be when Developmental Testing and Evaluation (DT&E) will occur to provide feedback to the PM on the progress of the system design and provide information on the adequacy of the program to meet system capability requirements. Successful completion of product prototype testing will normally be the basis for entering low rate initial production (LRIP). Independent operational testing and Evaluation (OT&E) will normally also occur during EMD. OT&E is performed by the component service’s operational test agency and is designed to validate that the system achieves its intended operational mission (DODI 2015).

During EMD, “the PM finalizes design of product support elements and integrates them into a comprehensive product support package” (DODI 2015). Product support and performance testing will be verified through reliability, availability, and maintainability (RAM) testing to make sure support packages and system design meets system life-cycle requirements.

Milestone C (MS C) is the point at which the program is reviewed for entrance into the P&D phase of the JCIDS/DAS process. The general criteria for entry into P&D is that the system demonstrate that the production design is stable and that it will meet system requirements based on successful completion of DT and OT events (DODI 2015). The MDA will document the MS C decision in an ADM at which time the system will proceed into the P&D phase.

Due to the limited scope of the project, the TECHMAN team used an abbreviated EMD phase that consisted of completing the prototypes and performing developmental testing. Due to the limitations of the Lego Mindstorms system, the TECHMAN is not

suitable for actual operational environments, and due to time and financial constraints, the TECHMAN team did not perform operational testing on the prototypes.

6. Production and Deployment Phase CONOPS

The P&D phase is to produce and deliver requirement-compliant products for use by the component service (DODI 2015). During the P&D phase “the product is produced and fielded for use by operational units” (DODI 2015). During this phase, LRIP and full-rate production decisions are made to support operational fielding of the system. System sustainment and support activities are implemented and carried out for the life of the program. During this phase, system errors and deficiencies should be identified and corrected prior to proceeding to full rate-production. These errors and deficiencies along with their mitigation strategies should be captured in the system CONOPS to ensure implementation and correction in future products (DODI 2015) (Edson and Frittman 2010).

The TECHMAN team omitted the P&D phase due to the limitations of the Lego Mindstorms system and due to time and financial constraints.

7. System-Specific CONOPS

The system requirements were developed based upon the high-level CONOPS. The system CONOPS was used to translate capability gaps into system-specific requirements and KPPs. These requirements formed the basis for an analysis of alternatives and selection of the best system design as MS A. With the system design selected, the high-level CONOPS evolved into a system-specific CONOPS. The CONOPS continued to evolve as the system proceeded through the TMRR and EMD phases. It was treated as a living document and updated throughout the acquisition life-cycle to communicate user needs and system requirements to system developers, system integrators, system testers, and program budget analysts to ensure that the RCS met the stakeholder needs and requirements.

Technology limitations were identified during the TMRR phase. The CONOPS was updated to match the more mature understanding of the capability to be delivered and facilitate trade discussions that resulted in trades necessary to ensure an affordable system.

Further refinement of the CONOPS occurred during the EMD phase as hardware and software designs were completed and prototypes were built and tested to verify compliance with capability requirements. Sustainment strategies and training materials were developed, and operational testers and evaluators developed test scenarios based on the CONOPS.

8. Operational Concept

When performing ground mobile or foot patrol operations, ground forces of the U.S. Army and Marine Corps face many hazards during field combat operations. Some of the hazards faced by these forces manifest themselves as IEDs or CBRNE objects placed by enemy forces in the operational area. Radiological objects could take the form of a nuclear device, or radiological waste (a so-called "dirty bomb") placed in the area of operation. When these hazards are encountered, American forces need a method to locate, identify, and dispose of the hazard.

This capstone project developed an RCS to locate, identify, and remove simulated hazards that represent what may be encountered by U.S. ground forces. The RCS must have a means for ground forces to locate potential radiological hazards in the operational area. A combination of radiological sensors would be used to identify the hazard once it is located. After the radiological hazard has been identified, it must be properly neutralized and disposed of. Due to the limitations of the exercise, inert "hazards" and sensors that can detect them were used in place of hazardous targets.

9. Capability Gaps

United States forces have a need for a system with a long standoff distance to locate, identify, and neutralize hazards to ground combat troops and support personnel.

While there are many handheld systems to locate and identify known hazards, these systems place the operator and personnel at risk while performing the hazard location and identification tasks. A system that operates at a distance could accomplish the same mission tasks while limiting the forces exposure to known or potential hazards. The use of autonomous systems to accomplish the hazard identification task will limit battlefield casualties and keep a greater number of forces in the fight.

B. CAPABILITY NEEDS STATEMENT

The Department of Defense needs a teleoperated or autonomous system that will locate, identify, and neutralize radiological hazards without endangering the system operators or other personnel. The system must be capable of traversing irregular terrain while locating, neutralizing, and removing radiological hazards. The system must be readily transportable, reusable, and capable of neutralizing multiple radiological hazards. The system must render radiological hazards harmless and safe for the operators and military personnel to operate or pass through the area after it has cleared the area.

1. Design Reference Mission

The DRM test area, shown in Figure 7, was randomly populated with vials that simulate radiological hazards. For testing and evaluation purposes, both robots ran through identical randomized courses so that comparisons could be made between the two systems.

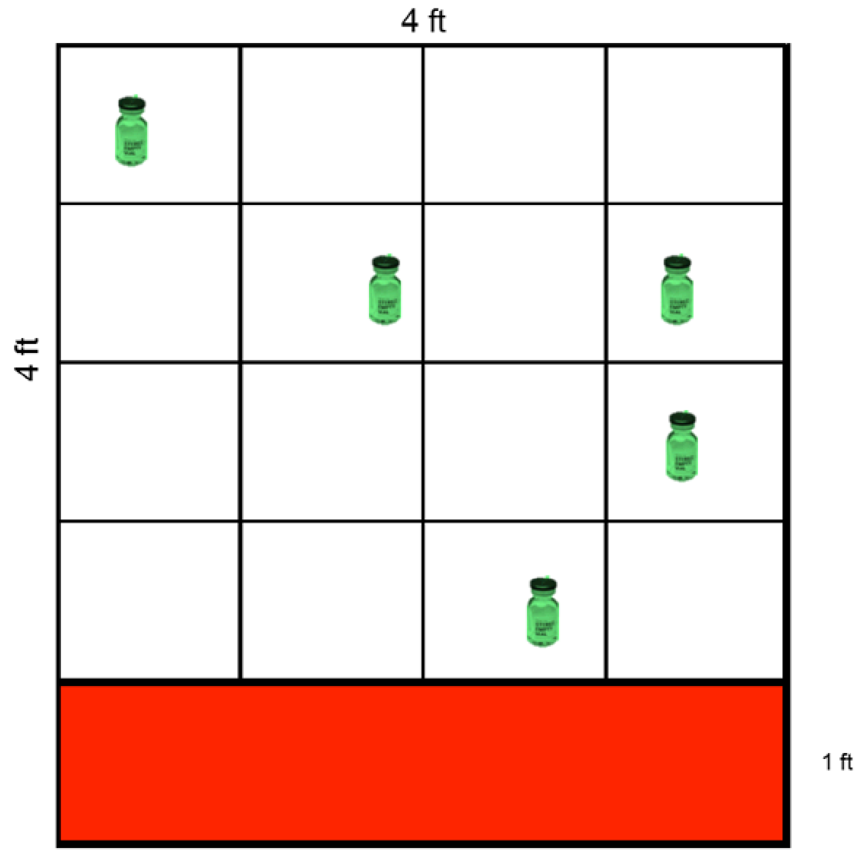


Figure 7. DRM Test Area for RCS

At the beginning of the evaluation, the operator activated the robot and placed it in the start position. The time to recover each vial was recorded. The original plan was to have the UGV identify if the vial was hazardous or not. This was to be simulated by two contrasting colors of vials and the color sensor on the UGV. However, it became evident that the color sensor could not distinguish the color difference due to sensor position and interference with the claw used to secure the vial. This effort was re-scoped with the new mission to recover all vials and place them in the designated disposal area. After clearing and stowing a vial, the UGV returned to the test area to clear the remaining vials. The test was complete and the timer was stopped after all of the vials were removed from the test area.

2. Functional Description

Figure 8 shows the system functional description (SV-4) for the RCS. The overarching mission function performed by the system was the clearance of simulated radiological vials. The SV-4 shows the decomposition of this overarching mission function into sub-functions.

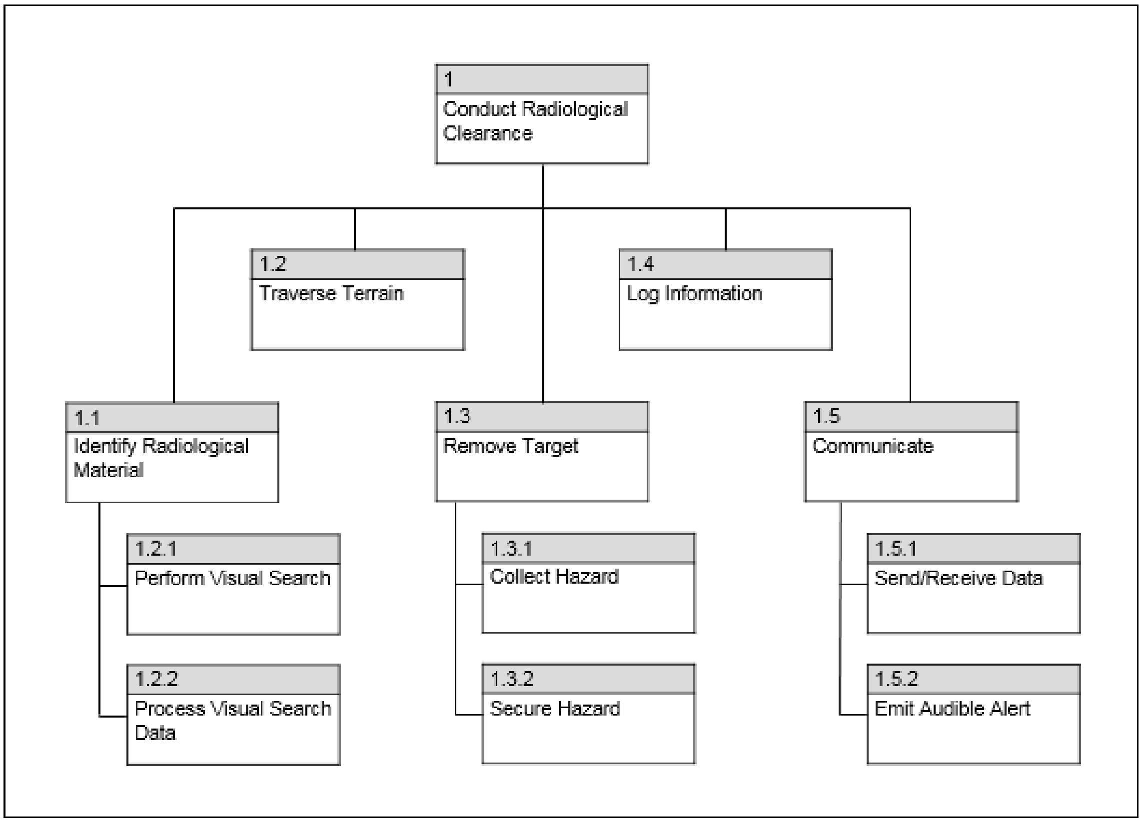


Figure 8. System Functionality Description (SV-4) for the RCS

3. Operational Environment

Table 1 provides a summary of the operational environment in which the RCS is expected to conduct radiological clearance operations. The operational environment will be secure with high visibility and in the absence of high wind or heavy rain. The RCS is not expected to operate on low-friction surfaces such as mud, ice, or snow-pack.

Table 1. RCS Operational Environment

Characteristic	Description
Surface Conditions	Concrete, blacktop, gravel, or forest floor. Less than 30% grade. Not expected to operate in mud, standing water greater than 25 millimeters deep, ice, or snow-pack.
Temperature	Negative 40 degrees Celsius to positive 60 degrees Celsius.
Precipitation	Less than 1 inch per hour of rain, wind blown under wind conditions shown. Not expected to operate in snow or sleet.
Wind	Less than 30 mile-per-hour sustained wind speed with gusts not greater than 50 miles-per-hour.
Visibility	Between 2000 and 200 lumens measured at the surface. Fog conditions with greater than 5-mile of visibility.
Security	Operationally secure location. Not expected to survive ordnance, small-arms fire, blunt force attack, or any other form of hostility. Operator is not expected to operate the system within a hostile environment.

4. Mission Success Requirements

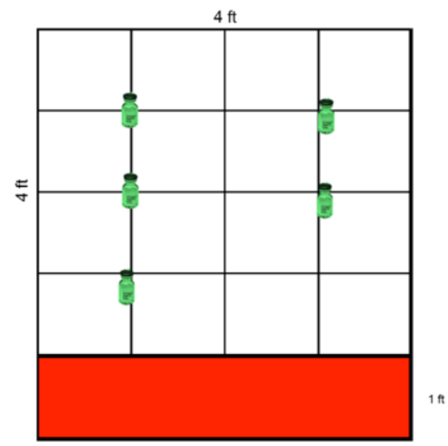
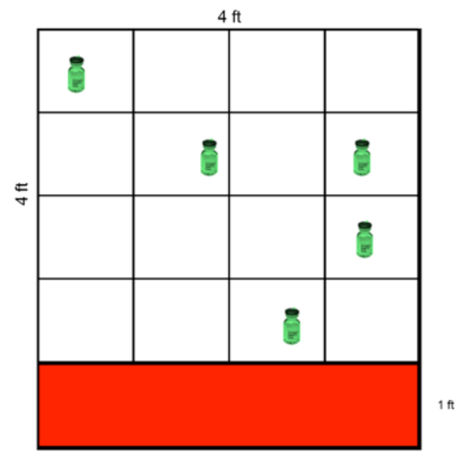
Initially, to achieve mission success, the RCS was to secure 95% of radiological targets (with 80% confidence), demonstrate a 75% probability of achieving this mission within two hours where the area-of-operation is 400 square-feet and contains area-of-operation containing 10 radiological samples and 10 non-radiological samples. The RCS shall also require not more than one operator and one set of spare batteries with charger and accomplish mission success within full range of expected operational environments. However, during testing, the mission area was reduced to 16 square-feet and five radiological samples due to the inability of the ACV to operate in a fully autonomous mode and the color sensors inability to clearly distinguish vial colors.

5. Use Cases

The DRM included two specific use cases. These use cases were designed to demonstrate the full range of system requirements. Environmental conditions, such as wind, rain, fog, and extreme temperatures, were beyond the scope of this capstone project

and not included in the use cases. Table 2 lists the objective, description, and data collected for the target arrangement for each use case.

Table 2. DRM Use Cases for the RCS

Use Case	Arrangement of Targets
Standard Nominal Clearing Test **UC-1 Autonomous Search** **UC-2 Teleoperated Search** **Objective**: To give a baseline comparison of performance and reliability for autonomous and teleoperation. **Description**: 5 targets placed in a specific pattern in a 4-foot by 4-foot area. RCS starting point is within the corral. RCS starts the mission with new batteries. **Data Collected**: Time to clear area, number of targets returned, target identification category, number of batter changes, and system failures or anomalies.	
Non-Standard Clearing Test **UC-1 Autonomous Search** **UC-2 Teleoperated Search** **Objective**: To give a Non-Standard mission representative test and ensure no bias between autonomous and teleoperation. **Description**: 5 targets placed in a random pattern in a 4-foot by 4-foot area. RCS starting point is within the corral. RCS starts the mission with new batteries. **Data Collected**: Time to clear area, number of targets returned, target identification category, number of battery changes, and system failures or anomalies.	

C. SYSTEM REQUIREMENTS

1. Overall System Requirements

Table 3 provides a summary of the overall system requirements for the RCS. TECHMAN is to be a single operator system. This single, trained operator must be able

to transport, set-up, and operate the system within the full range of expected operational environments. The TECHMAN system must conduct the DRM and achieve the mission success requirements on a single set of new batteries and while using teleoperation, autonomous operation, or some combination of the two.

Table 3. Overall System Requirements for the RCS

Attribute	Requirement
Weight	Two containers, less than 35 pounds-per-container.
Batteries	6 size AA batteries, rechargeable or non-rechargeable.
Battery Replacement	Less than 2 minutes for trained operator.
Battery Life	Greater than 2 hours of mission time.
Operator	Not more than one operator to transport, set-up, and operate.

2. Teleoperated Requirements

Teleoperation may improve operational efficiency when the operator has specific knowledge regarding the location of radiological hazards. The RCS shall provide the ability for teleoperation when there is unobstructed line-of-sight at a range of 30 meters and under, which is the full range of expected operational environments.

3. Autonomous Requirements

Autonomous operation is required when unobstructed line-of-sight is not available for teleoperation or the operation must maintain greater than a 30 meters of standoff. Autonomous operation may be combined with teleoperation to ensure full coverage of the area of operation. The RCS must be capable of logging the search area covered during teleoperation and avoiding redundant search coverage.

4. Capability Development Document

Table 4 contains the system requirements that would be included in the CDD within JCIDS/DAS. The requirements are divided into four high level operational tasks.

The operational tasks, which are similar to critical operational issues and criteria (COIC), are the “bottom line standards of performance that, if satisfied, signify the system is operationally ready to proceed beyond the milestone decision” (Department of the Army 2011). The requirements related to the operational tasks are KPPs, key system attributes (KSAs), and additional performance attributes (APAs).

KPPs are “performance attributes of a system considered critical or essential to the development of an effective military capability. Failure of a system to meet a validated KPP threshold value triggers a review by the validation authority and evaluation of operational risk and/or military utility of the associated system(s) if KPP threshold values are not met. The review may result in validation of an updated KPP threshold value, modification of production increments, or recommendation for program cancellation” (JCIDS Manual D-A-1).

KSAs are “performance attributes of a system considered important to achieving a balanced solution/approach to a system, but not critical enough to be designated a KPP” (JCIDS Manual D-A-1).

APAs are “Performance attributes of a system not important enough to be considered KPPs or KSAs, but still appropriate to include in the CDD or CPD are designated as APAs” (JCIDS Manual D-A-1).

The requirements are expressed using Thresholds (T) and Objectives (O). “Performance below the threshold value is not operationally effective or suitable or may not provide an improvement over current capabilities” (JCIDS Manual D-A-1). “The objective value is the desired operational goal achievable but at higher risk in life cycle cost, schedule, and technology” (JCIDS Manual D-A-2).

The DOD JCIDS Manual requires all systems to have six mandatory KPPs which are; Force Protection, System Survivability, Sustainment, Net Ready, Energy, and Training. For the purposes of this project only the Energy KPP was considered. The other mandatory KPPs would be waived for this type of system for being outside the scope of this project. Waiving mandatory KPPs requires approval from the appropriate certifying or endorsing organization (JCIDS Manual D-A-4)

Table 4. Capability Development Document

Operational Task	Requirement Number	Requirement	
Operational Task 1: The Robot shall pass and receive mission information	KSA 1	The robot shall notify the operator of system malfunctions.	T=O
	KSA 2	The robot shall store a mission log file for retrieval by the operator.	T=O
	KSA 3	When returning a vial to the corral, the robot shall play a distinct sound for a "hazardous vial" and a different sound for an inert vial.	T=O
Operational Task 2: The Robot shall operate in its intended environment	KPP 1 - Energy	Starting with fully charged batteries, the robot shall run for the specified amount of time without swapping batteries.	T: 2 hours, O: 3 hours
	KPP 2 - Transport	The system shall be transportable in the specified number of containers; each container shall be transportable by a single Solder.	T: Two containers, with the weight of each container not to exceed 35 lbs. O: One container, with a weight not to exceed 35 lbs.
	KSA 4	6 AA batteries or rechargeable equivalent shall power the robot.	T=O
	KSA 5	The system shall operate in a manner safe to its operators.	T=O
	APA 1	Batteries shall be replaceable within two minutes.	T=O
	APA 2	The system shall comply with the FCC's requirements for a Class D device. Harmful interference, as defined in the FCC rules, shall not prevent the system from accomplishing the mission.	T=O
	APA 3	The system shall be operated by not more than one servicemember	T=O
Operational Task 3: The Robot shall propel itself under its own power, including while carrying vials	KSA 6	The robot shall traverse terrain of smooth concrete or blacktop surfaces	T: Concrete or blacktop with coefficient of friction between 0.2 - 0.9 O: Gravel or forest

Operational Task	Requirement Number	Requirement	
			floor
	KSA 7	The robot shall be able to change its heading to any 360 degree orientation	T=O
Operational Task 4: The Robot shall clear a given area of radiological threats	KPP 3 – Clearing Area	The robot shall clear a rectangular area (the “target area”) of a defined size.	T: 16 square feet O: 625 square feet
	KPP 4 – Vial Transport	The robot shall secure all vials and return them to the corral for disposal by trained personnel and a separate system at the required rate.	T: P (return standard size vial) = 95% O: P (return standard size vial) = 99%
	KSA 8	The robot shall distinguish a “hazardous” colored vial from vials of other colors with a specific probability of distinction.	T: P (distinction): 90% O: P (distinction): 95%
	KSA 9	The system shall detect vials under fluorescent lighting conditions (between 2000 and 900 lumens).	T=O
	KSA 10	A continuous blue marking not less than 1 inch thick shall surround the target area.	T=O
	KSA 11	The start and end point for the robot shall be a 1’ by 4’ red colored tile called the corral. The corral shall be located at a corner of the target area.	T=O
	KSA 12	The system shall have the specified probability of completing a 2 mission hours without an essential function failure.	T: 0.75 Probability of completing a 2 hour mission without an essential function failure O: 0.9 Probability of completing a 2 hour mission without an

Operational Task	Requirement Number	Requirement	
			essential function failure
	KSA 13	The system shall have the specified probability of completing 2 mission hours without a system abort	T: 0.95 probability of completing a 2 hour mission without a system abort O: 0.99 probability of completing a 2 hour mission without a system abort
	APA 4	The system shall not exceed the specified man maintenance hour / operating hour (MMH/OH) ratio	T: 0.04 MMH/OH O: 0.015 MMH/OH
	APA 5	The system shall pass the Standard Nominal Test Pattern according to the threshold and objective values defined by that test pattern.	T: See the SNTP O: See the SNTP

III. ARCHITECTURE DEVELOPMENT

A. DEVELOPMENT METHODOLOGY

The architecture development methodology for TECHMAN began in the requirements analysis phase. The prime directive provided a basis of establishing the right requirements for the system. A functional analysis was conducted to determine necessary system functions while remaining within the requirement constraints. The functional analysis produced a functional architecture. Form should follow function and thus, the physical analysis followed the functional architecture. The physical analysis produced the physical architecture. The system architecture was modeled and validated by Innoslate (developed by SPEC Innovations). Furthermore, two prototypes that were designed, built, and tested provided insight into architecture development.

1. Black Box Theory

The black box theory was useful in developing the functional and physical architectures. In the black box theory, interacting objects are depicted as generic objects that require inputs and produce outputs, but whose inner workings are unimportant. Inputs and outputs are classified as energy, matter, material wealth, and information (EMMI). The object performs a mechanism that converts input EMMI to output EMMI. Output EMMI either provides inputs to another object or is dissipated beyond the boundary of the object as a loss (heat, exhaust, noise, etc.). Figure 9 is an adaptation from an SE4151 Systems Architecting and Design Lecture on Objects, Boundaries, and Interactions given by John M. Green. The figure shows the flow of EMMI through an object. The object’s internal control mechanisms do not need to be fully understood. However, the interactions of EMMI between system objects must be understood to ensure proper integration of system components in order to achieve emergent behaviors in a system to accomplish the prime directive.

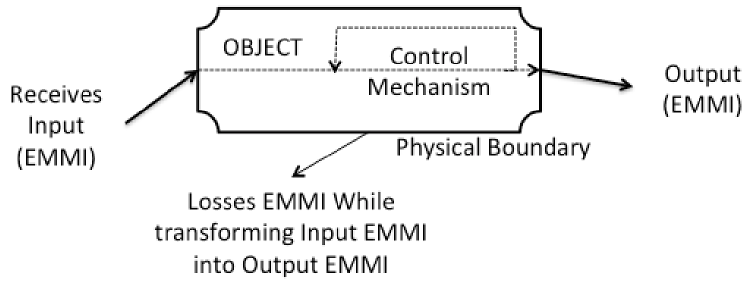


Figure 9. Black Box Theory Diagram

The TECHMAN architecture treats the system objects within the physical architecture as black boxes that provide EMMI inputs/outputs throughout the integrated system structure. The use of Lego Mindstorms components becomes an integration exercise. The EMMI inputs and outputs of these components in the TECHMAN system and interactions between each object are described later in this chapter.

2. Modularity

One advantage of using Lego Mindstorms for TECHMAN is modularity. The components can be reconfigured to suit the needs of various system objectives. The piece parts can be disassembled and reassembled to suit the needs of follow-on capstone efforts. Software code can also be reused and refined in follow-on efforts. Geographical constraints are minimized by the ease of shipping physical components and the electronic accessibility of source code.

B. FUNCTIONAL ARCHITECTURE

The functional architecture outlines what the system must do. For TECHMAN, the prime directive is to safely and reliably identify and clear an area of containers representing either hazardous or inert materials. The enabling functions for the system include but are not limited to: transport, sense, identify, secure, report, and signal. These functions are organized in the functional architecture.

1. Functional Decomposition

Table 5 shows the allocation of functions from the SV-4 from Figure 8 to the system requirements, and it also provides a description of each function and the requirements associated with it.

Table 5. Functional Allocation to Requirements

Function	Description	Req.
1 Conduct Radiological Clearance	This is the overall function of the system. All sub functions support this overarching function to safely and reliably distinguish and clear an area of radiological and inert vials.	Operational Task 4
1.1 Identify Radiological Material	This function shall enable the system to distinguish a hazardous vial from a non-hazardous vial.	KSA 8
1.1.1 Perform Visual Search	The system shall visually search for vials using onboard sensors. This function provides situational awareness and supports the Identify function.	KSA 9
1.1.2 Process Visual Search Data	This function enables the system to distinguish the difference between radiological and inert vials.	
1.2 Traverse Terrain	The system shall provide its own source of propulsion.	KSA 6 KSA 7
1.3 Remove Target	The system shale locate, secure, and carry the target out of a specified area and places the target into the corral	KPP 4
1.3.1Collect Hazard	Collecting the hazard involves sensing the hazard, positioning the vehicle, and securing the hazard.	KSA 9 KPP 4 APA 5
1.3.2 Secure Hazard	The system shall approach and secure the vials for safe transportation to the corral.	KSA 9 KPP 4 APA 5
1.4 Log Information	The system shall maintain a log of operations performed with time data in order to determine process improvements in the future or corrective actions for issues that arise.	
1.5 Communicate	The system shall communicate vital information to the operator. Sub-functions will provide the inputs to the communications made to the operator.	Operational Task 1

Function	Description	Req.
1.5.1 Send/Receive Data	The system communicates status of the vehicle and the secured target.	KSA 1 KSA 2 KSA 3
1.5.2 Emit Audible Alert	The system shall emit an audible alert indicating if the target is hazardous.	KSA 3

2. Functional Flow Block Diagram

The functional architecture was shown previously as a function hierarchy diagram in the SV-4 in Figure 8. These functions provide a basis for developing the functional flow block diagram (FFBD). The FFBD aids in model development and simulation of system behaviors. Figure 10 shows the FFBD for a RCS nominal mission.

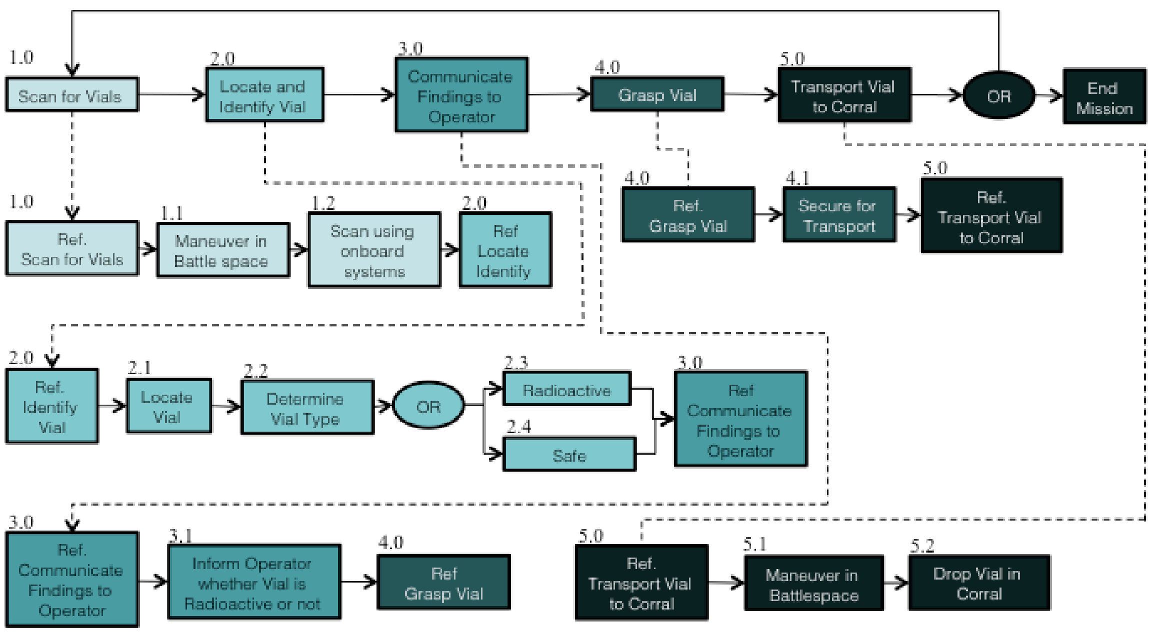


Figure 10. RCS Functional Flow Block Diagram

C. PHYSICAL ARCHITECTURE

The physical architecture designates the system components necessary to accomplish the actions in the functional architecture. While the functional architecture outlines what to do, the physical architecture outlines how to do it.

1. Physical Architecture Hierarchy Diagram

Figure 11 shows the physical architecture of the TECHMAN system. It is comprised of vehicle hardware, logistics support, test and evaluation, and software. The vehicle hardware includes the EV3 brick, ultrasonic sensor, color sensor, touch sensor, motors, and other Lego structural components. The logistics support produces the operation guide and technical documents. The test and evaluation demonstrated if the TECHMAN system accomplished the necessary functions to achieve KPPs and the prime directive. The software component provides the necessary logic for the devices to perform their mission based on the inputs it receives from onboard sensors and applicable inputs from the operator. Table 6 lists and describes the active physical objects contained in the TECHMAN system.

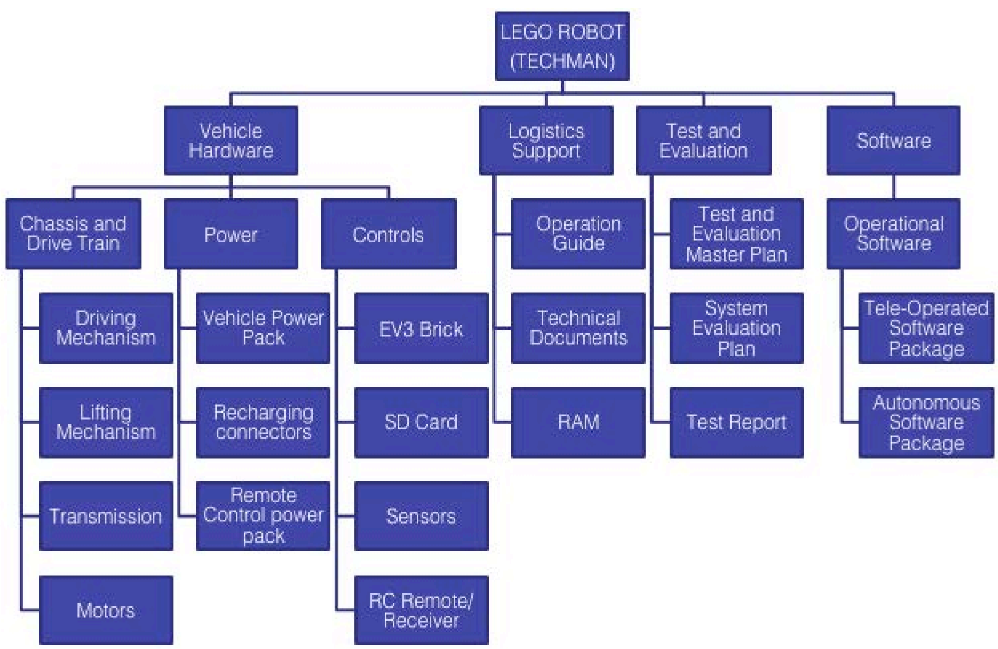
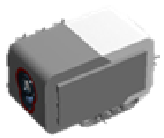
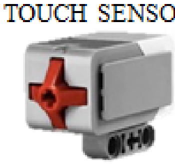


Figure 11. Physical Architecture

Table 6. Physical Object Descriptions

OBJECT	DESCRIPTION
OPERATOR 	The operator will ensure the batteries in the EV3 brick are fully charged before mission begins. The operator will place the vehicle in its starting location and monitor the vehicle during mission execution. The operator will remotely control the teleoperated variant.
EV3 BRICK 	The EV3 Brick is the LEGO MINDSTORM control center. It sends commands to the motors and receives inputs from the sensors. It can display the system status including battery level, Wi-Fi and Bluetooth connection status.
ULTRASONIC SENSOR 	The ultrasonic sensor is a digital sensor that uses reflected sound waves to measure distance to objects in its path. It can detect objects up to 99 inches away with an accuracy of +/- 0.394 inches.
COLOR SENSOR 	Recognizes 7 different colors and light intensity. Sample rate of 1Hz. Three modes: color mode, reflected light intensity mode, ambient light intensity mode.
LARGE REGULATED MOTOR 	Powerful and precise robot action. The large motor is a powerful "smart" motor. It has a built-in rotation sensor with 1-degree resolution for precise control. Runs at 160-170 rpm with 20 Ncm torque and stall torque of 40 Ncm.
MEDIUM REGULATED MOTOR 	The medium regulated motor is compact in size and provides a faster response. The medium motor includes a built-in-rotation sensor but is smaller and lighter. Runs at 240-250 rpm with 8 Ncm torque and stall torque of 12 Ncm.
TOUCH SENSOR 	The touch sensor recognizes three conditions: touched, bumped, and released. The touch sensor is an analog sensor.
FIELD COMPUTER 	Field computer will receive communications from the EV3 brick. It will display relative status information for the operator. It also contains the program file that gets loaded to the EV3 brick prior to mission execution.
OPERATOR CONTROL UNIT Tablet/device 	For the teleoperated variant. The OCU sends drive commands to the EV3 brick.

The work breakdown structure (WBS) identifies the working levels of effort necessary to build the physical architecture. The WBS has been split into five views from Figure 12 through Figure 16.

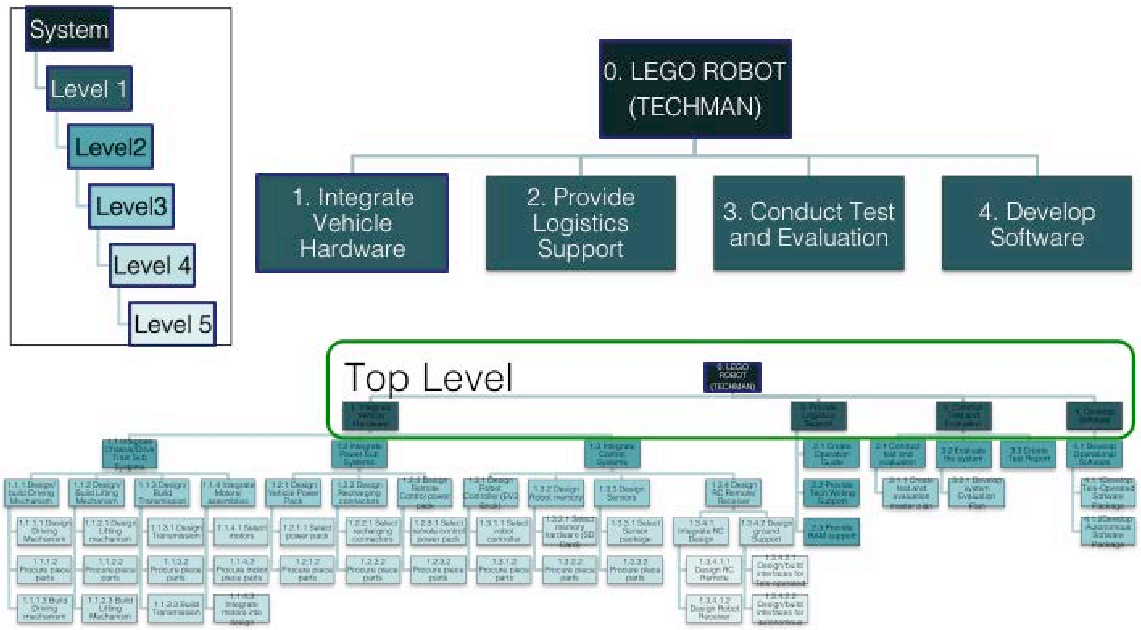


Figure 12. Work Breakdown Structure, View 1 of 5

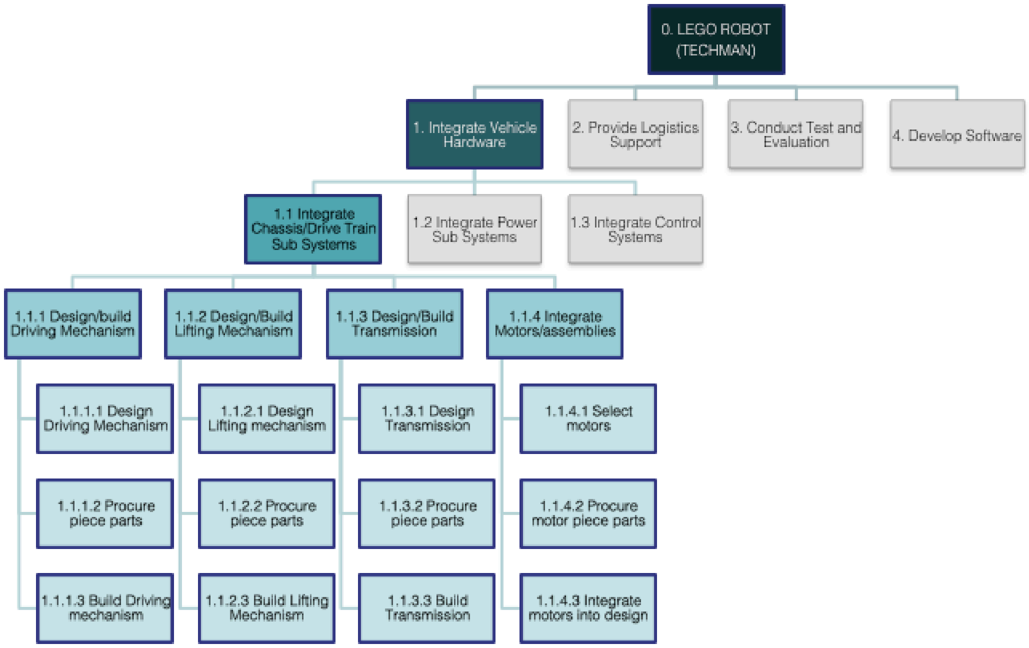


Figure 13. Work Breakdown Structure, View 2 of 5

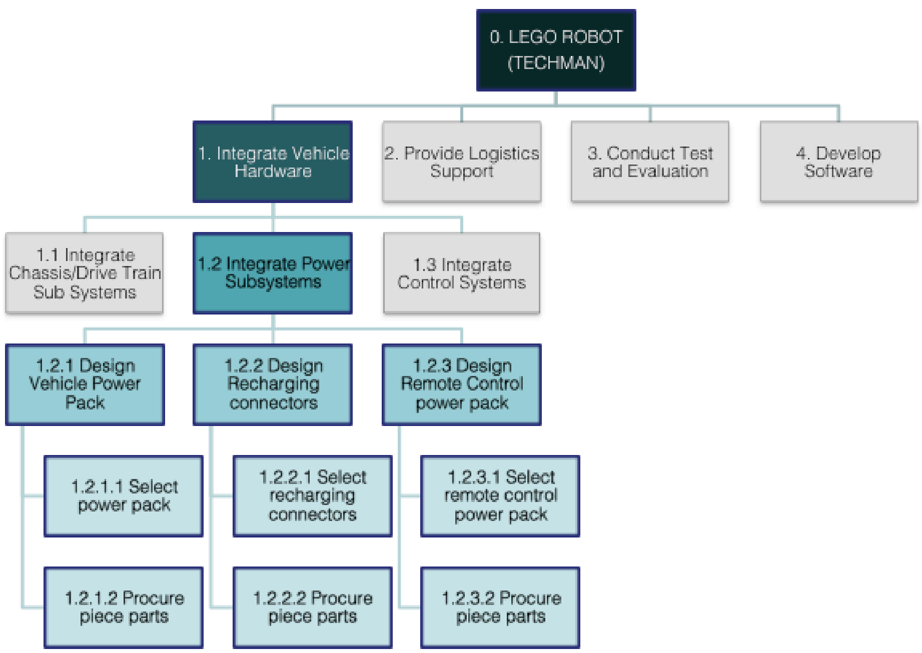


Figure 14. Work Breakdown Structure, View 3 of 5

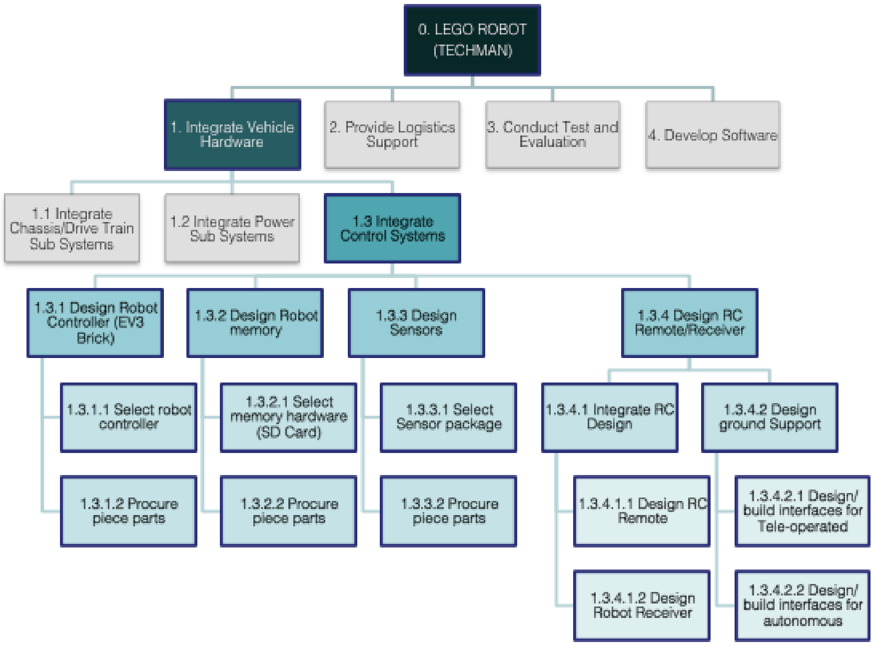


Figure 15. Work Breakdown Structure, View 4 of 5

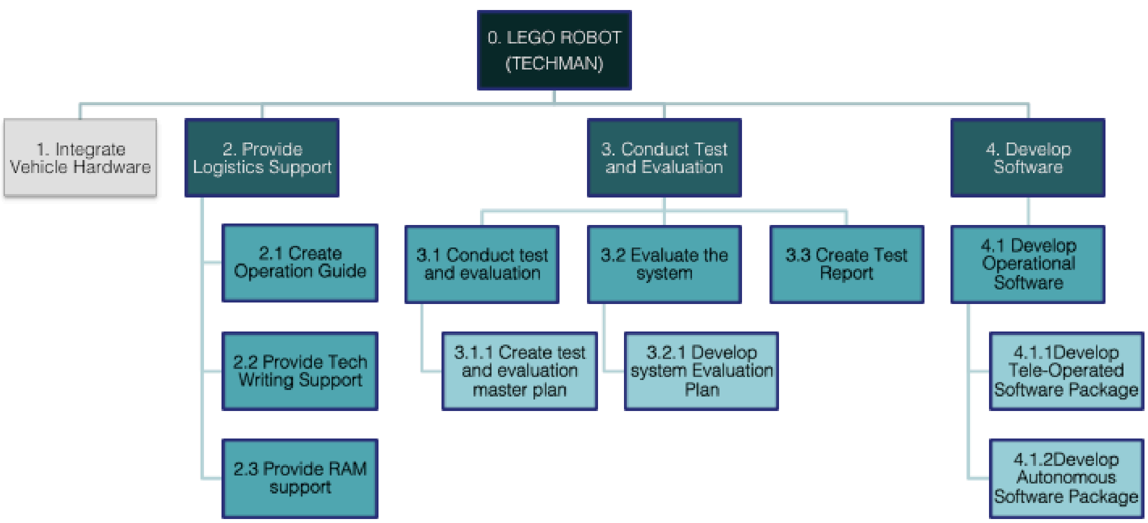


Figure 16. Work Breakdown Structure, View 5 of 5

D. ALLOCATED ARCHITECTURE

1. Integration of Functional and Physical Architecture

Figure 17 shows the interactions between the active objects of TECHMAN. The large motors receive energy from the EV3 brick. They provide the propulsion for the TECHMAN vehicle. The small motor receives energy from the EV3 brick. It provides the mechanical driver for opening and closing the claw that secures the vials. Each of the sensors (ultrasonic, color, and touch) receives energy from the EV3 brick and in turn sends information back to the EV3 brick in the form of a voltage output. The EV3 brick sends information to the Field Computer. The Field computer displays information to the user. The user sends physical inputs into the field computer and to the OCU on the teleoperated variant. The OCU sends information to the EV3 brick.

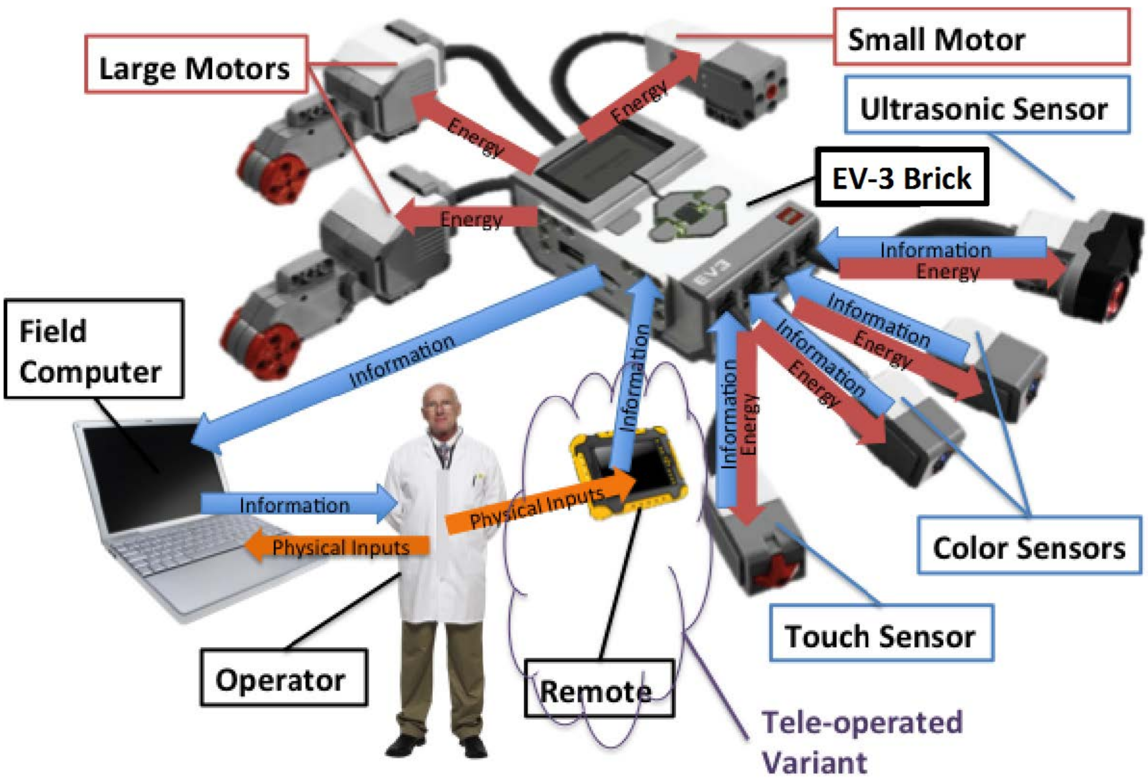


Figure 17. TECHMAN Component Diagram

2. Allocated Architectural Diagram

Table 7 lists the inputs, outputs, and function allocation for each of the active objects in the system.

Table 7. Functional Allocation and I/O of Physical Objects

OBJECT	INPUT	OUTPUT	FUNCTION
OPERATOR	Visual situational awareness, food, water	Inputs to the field computer and OCU	1, 1.5
EV3 BRICK	Power supply, transmissions from OCU, voltage from sensors	Voltage to motors and sensors, transmissions to field computer, audio alerts	All vehicle functions
ULTRASONIC SENSOR	Voltage from EV3, echo sound waves	Voltage to EV3, pulse sound waves	1.1.1, 1.3.1, 1.3.2
COLOR SENSOR	Voltage from EV3, light wavelengths	Voltage to EV3, source light beam	1.1.2
LARGE REGULATED MOTOR	Voltage from EV3,	Torque	1.2
MEDIUM REGULATED MOTOR	Voltage from EV3,	Torque	1.3.2
TOUCH SENSOR	Voltage from EV3, force	Voltage to EV3	1.3.2
FIELD COMPUTER	User inputs, source code updates, communications from EV3 brick	Display of information to user	1.5
OPERATOR CONTROL UNIT	Inputs from user. Depressing buttons, etc.	Information to EV3 brick transmitted wirelessly	1.5

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IV. UGV WITHIN THE JCIDS / DAS PROCESS

A. ANALYSIS OF ALTERNATIVES

Two AOAs were performed in support of this project. The first was the program-level AOA used to support the MS A decision. The second AOA performed was the subsystem level AOA. This AOA was used in the software decision for the TECHMAN system.

1. Program Level AOA

The program-level AOA was used to directly support the MS A decision and the JCIDS/DAS process. It is the AOA that would normally be used to determine the path of the program. This AOA was done simply as an exercise as this project was directed to use the Lego Mindstorms system from the beginning.

a. Initial Candidate Alternatives

Three candidates were considered in the program-level AOA. The candidates were:

- Status Quo – The status quo is assuming the service member find and clears the vials by hand.
- Modification of a legacy system – Modification of a legacy system would be taking an already fielded system and modifying it to meet the new user need. For this AOA the currently fielded Talon system was considered as the legacy system.
- New developmental system – The new developmental system is the option that the team develops a new system. This option is what the TECHMAN system falls under.

b. Evaluation Measures

The team developed evaluation measures that were used to determine the best option to take. The evaluation measures included:

- capability of the system to clear standard radiological vials
- ability to provide safe standoff distance for servicemembers from vials
- capability of the system to operate teleoperated and autonomous
- transportability of the system to the mission site
- cost of the system

Decision Factors

Table 8 depicts the three options against the evaluation analysis and cost analysis. As can been seen in the table, the status quo is eliminated due to not providing standoff for service members. Modification of the Talon would likely be effective in completing the mission however the system is heavy and difficult for dismounted troops to transport. Early analysis of the TECHMAN system and market research showed the system would be capable of meeting the effectiveness measures and be light enough for transport by one service member. The team conducted a market research by viewing the capabilities of other Lego Mindstorms systems people had posted on the Internet.

Table 8. AOA Decision Analysis

	Status Quo (Servicemembers retrieving vials by hand)	Modification Legacy System (Talon)	New Developmental System (TECHMAN)
Effectiveness Analysis	Will not provide standoff for servicemembers	Will meet all of the evaluation measures but a large and heavy system. -Not transportable by one servicemember	Research shows the system will be capable of meeting evaluation measures
Cost Analysis	No additional system cost but requires additional servicemembers, raising overall cost	Highest overall program cost	Lowest overall program cost

Cost was considered for this analysis; however, it is not a fair comparison due to the nature of a simulated system being built from Lego Mindstorms verses a real fielded military system. The cost of both the initial system and support throughout the life-cycle of the Talon system is orders of magnitude larger than the TECHMAN system.

c. Final Decision

The TECHMAN was selected as the system to use due to its ability to meet requirements, its ease of transportability, and its lower cost.

2. Subsystem-Level AOA

A subsystem AOA was used to select the software environment used. The team was offered licenses and documentation for the ROBOTC Robotic Operating System, or documentation for the community supported LeJOS operating system. Each system included an Integrated Development Environment, hardware compilers, and support libraries. Since ROBOTC is based around the C programming language and LeJOS is based around the Java programming language, the team could only select one whole

environment or the other. Using parts from ROBOTC and parts from LeJOS is not supported by either system.

This additional AOA was not completed to directly support JCIDS/DAS documentation but support the design of the system.

a. Initial Candidate Alternatives

Two candidates were considered in the subsystem-level AOA. The candidates were:

- using leJOS for the Operating System
- using ROBOTC for Operating System

b. Evaluation Measures

The team developed evaluation measures that were used to determine the best option to take. The evaluation measures included:

- range of alternative Linux based operating system
- familiarity of software for programmers
- programming methods
- collaboration ability
- ability to control TECHMAN

c. Decision Factors

The team analyzed the two approaches against evaluation measures and selected the preferable option based on team judgment. For most of the measures, one of the two options as preferable. For some of the measures, however, neither option was clearly preferable. The results of the analysis are shown in Table 9.

Table 9. Subsystem AOA Decision Analysis

Measures	ROBOTC	leJOS	Preferable Option
Language	Based on ANSI C	Java SE Embedded	leJOS
License	Proprietary Commercial Software	Open Source	No Preference
Cost Analysis	$49 - $139 Per Seat	Free	leJOS
Operating System	Windows Only	Windows Linux Mac	leJOS
Supported Platforms	Lego Mindstorms VEX Robotics Arduino	Lego Mindstorms	No Preference
Runtime Environment	Native (Hardware Specific)	Java Virtual Machine	No Preference
Integrated Development Environment (IDE)	ROBOTC Proprietary	Eclipse IDE	leJOS
Source Control	3rd. Party External	Plug-in Support	leJOS
Support	Official Paid (Included with License) Community	Community	ROBOTC
Maturity	Stable Release	Beta Release	ROBOTC

d. Final Decision

LeJOS was selected as the system to use due to developer familiarity with Java programming language, and the ability to support multiple development environments across multiple systems, including support for our source control platform. The team also did not consider the fact that LeJOS is beta software with community support to be insurmountable problems for this effort. However, on a full-scale development effort, this

may have tipped the scales towards ROBOTC due to its official support and stable releases.

B. RISK ANALYSIS

Risks were identified, managed, and assessed throughout the life of the project. Identified risks fell into two categories: project risks and technical risks. Project risks are high-level risks that impact cost and schedule. Technical risks are those that relate directly to the TECHMAN system.

1. Risk Identification and Analysis

All of the project team contributed to identifying and managing risks. The WBS was the top level starting point for identifying risks. A top-level and low-level identification approach was used such as brainstorming amongst the team and technology analysis.

Once the risks were identified, they were analyzed and put into a risk category of project or technical. For each risk identified the root cause, likelihood of occurrence, and the consequence of that occurrence were determined. Table 10 is the guide for the likelihood of occurrence and Table 11 is the guide for the determining the consequence. Figure 18 will be used to determine the rating of each risk.

Table 10. Risk Likelihood Levels

Level	Likelihood	Probability
1	Not Likely	~10%
2	Low Likelihood	~30%
3	Likely	~50%
4	Highly Likely	~70%
5	Near Certainty	~90%

Table 11. Risk Consequence Levels

Level	Cost Impact	Schedule Impact	Technical Impact
1	Minimal or None	Minimal or None	None
2	Increase < 3% of Budget	Slip < 1 Month	1 Requirement Not Met
3	Increase < 6% of Budget	Slip < 2 Months	2 Requirements Not Met
4	Increase < 9% of Budget	Slip < 3 Months	3 Requirements Not Met
5	Increase > 9% of Budget	Slip > 3 Months	4 Requirements Not Met

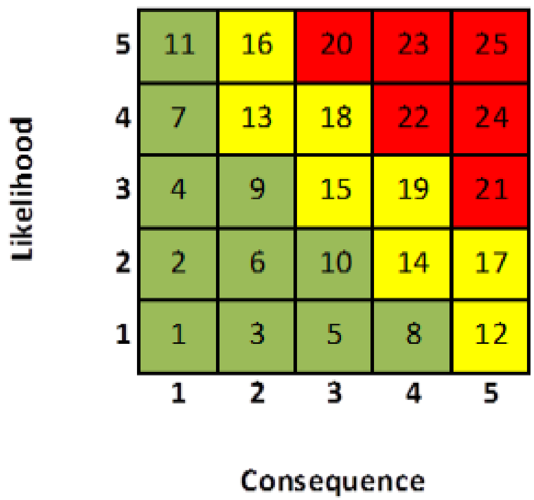

Figure 18. Risk Matrix

After the risks were identified and scored, a decision was made of how to avoid, reduce, eliminate or control the risk. The identified risk was tracked using a database and managed using good engineering judgment. Team TECHMAN monitored and discussed the risks as the need arose. The risk scores were updated as their status changed.

2. Identified Project Risks

Table 12 shows the project risks as initially identified, along with their associated score, root cause, likelihood of occurring, consequence of occurring, and the mitigation taken.

Table 12. Project Risks

Risk	Root Cause	Likelihood	Consequences	Mitigation
Knowledge needed for Research Questions may not be acquired (Project Risk) Score – 20	Not gaining the knowledge to answer the questions while completing the project	5 – Due to the simulated nature and short time frame solid answer may not be found	3 - Not gaining the insight required and having a good report	Perform literature review to point the project in the right direction. Ensure the questions are able to be answered
Team not meeting delivery dates (Project Risk) Score – 15	Due to the short time period, location of team members and member's other time commitments may not get tasks done	3 – Members are committed to the project and team so likelihood of large delay is low	3 - Not getting the project done causing failure	Have a good schedule. Use EVM to track progress. Hold everyone responsible for tasks.

Due to the nature of using simulated systems and a simulated IPT some of the research questions could not be answered definitively. Developing the TECHMAN systems provided good insight and helped the team have a high level understanding of the information needed to answer the research questions.

The TECHMAN team was able to meet delivery dates for the project by setting and following an internal schedule. EVM was used to ensure the program was on track.

3. Identified Technical Risks

Table 13 shows the technical risks as initially identified with their associated score, root cause, likelihood of occurring, consequence of occurring, and the mitigation taken.

Table 13. Technical Risks

Risk	Root Cause	Likelihood	Consequences	Mitigation
Robots not meeting requirements (Technical Risk) Score – 22	Robots not having capability to meet requirements to due component limitations or time constraints	4 – Development has shown the robots may struggle to meet requirements	3 – The robot will not perform the mission as required	Continue component testing and software refinement.
Teleoperated Robot not having the required range to complete the DRM (Technical Risk) Score – 19	Bluetooth will not have required range. Test location does not have Wi-Fi; Wi-Fi will be brought to location.	3 – due to the unknown this risks is scored medium	4 - Testing will not be able to be completed	Go and test Wi-Fi at the test location before the DT testing.
Robots not being able to grab and transport vials during testing (Technical Risk) Score – 14	Using Legos has inherent limitations	2 – The vials are light	4 - Robot will fail mission	Component testing to ensure the arm is capable of carrying the vials
Autonomous robot being able to complete the mission without operator input (Technical Risk) Score – 18	Hardware or software not having the capability to perform the mission completely autonomously	4 – Issues have been found during component testing and software development	3 – The robot will require more input from the operator	Continue component testing and software refinement.
Software not functioning properly during testing causing a mission failure (Technical Risk) Score – 13	Short timeframe and small team writing software	4 – Software anomalies will likelihood be encountered	2 – buggy software can be dealt with in a DT environment	Component testing will find most bugs. Small bugs that required a system restart will not be a big deal in DT
Autonomous robot not finding the vials during testing (Technical Risk) Score – 22	Color sensors not being able to find vials due to lack of range or capability of distinguishing vial colors	4 – Issues have been found during component testing	4 – The robot will fail the mission	Continue component testing and software refinement. Use colors on the vials the sensor can find

The TECHMAN systems completed testing and had favorable results. During the design process and testing all except two of the risks were mitigated or did not come to fruition. The two risks that were realized were “robots not meeting requirements” and “autonomous robot being able to complete the mission without operator input.”

Due to limitations of the Lego Mindstorms hardware, the team needed to adjust the scope of our project. The search area was lessened dramatically (from 20 feet square to four feet square). Additionally, due to problems with path finding, the ACV could not return to a known position to start every run. As a result, the team allowed the ACV to seek and return one vial, then be restarted by the operator.

If the program proceeded past MS B, then the requirements could be changed to fit with the current capability of the system. The more likely case would be sufficient system refinements, either with the software or the hardware or both, to ensure the revised system would satisfy the original requirements of the user.

V. SYSTEM DESIGN

A. HARDWARE DESIGN

An early design decision made by the TECHMAN team was that the ACV and TCV should use identical hardware designs and differ only in software. This constraint was largely time-based; the team did not feel there was enough time to debug two hardware designs along with two software designs. The original hardware design as seen in Figure 19 was heavily influenced by Grabby, the robot proposed by Bagnall to demonstrate the EV3 Control Center program for debugging EV3 robots.

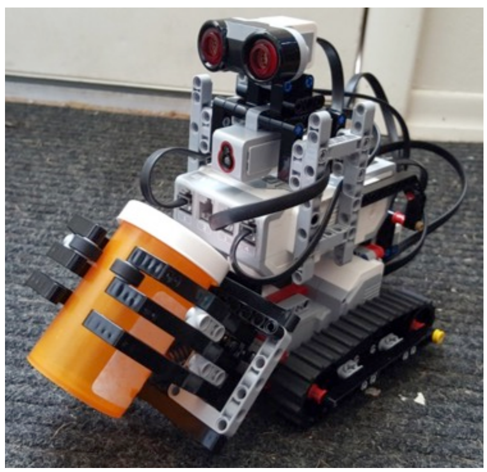

Figure 19. Early TECHMAN Design Prototype

The final version of the hardware design was an amalgamation of iterating experimental designs, sub-components from reference designs, modeling with Lego Digital Designer, and lessons learned from the initial design. The Digital Designer model can be seen in Figure 20. The resultant hardware was designed in a modular manner, allowing for rapid testing, evaluation, and reimplementation of sub-components as necessary. The final physical assembly can be seen in Figure 21 and Figure 22.

Figure 20. Digital Designer Model View

Figure 21. Final Hardware Assembly View 1

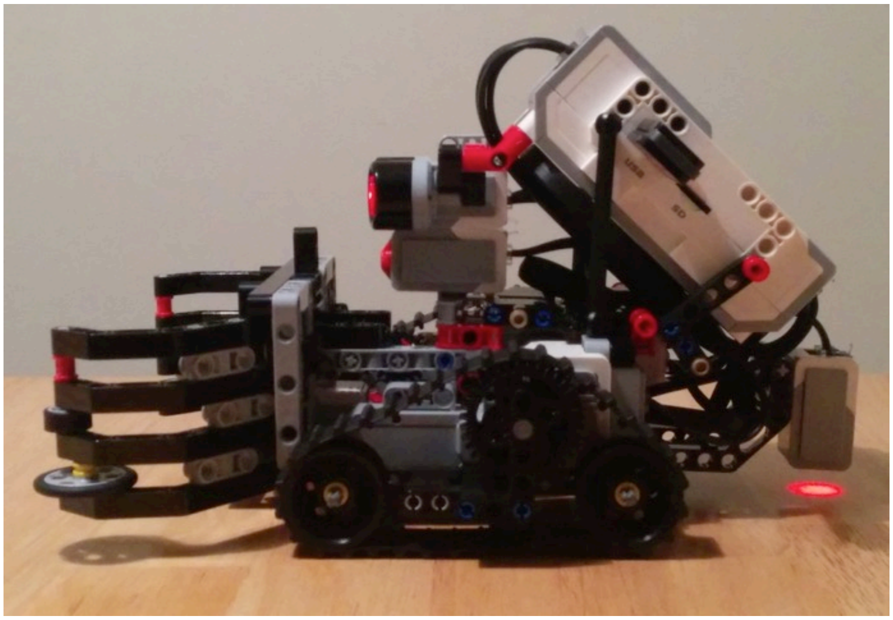
Figure 22. Final Hardware Assembly View 2

The most notable design change from the initial platform is the positioning of the EV3 brick and the track design. The original design utilized the EV3 as an integral part of the chassis resulting in substantial disassembly of the platform to change the power source. The original design also experienced problems with the tracks coming off. The final design used a triangle orientation, which eliminated the issue of losing the tracks. Unlike the initial design, which was primarily focused on the drivetrain, planning the final hardware design also included further consideration of sensor positioning. This was a crucial component of the platform.

The team also decided that both devices should use the same software environment. As mentioned in the AOA, the team selected leJOS because the higher familiarity the team had in working in Java than in C and because leJOS supports full IDEs that are compatible with other programming tools, notably our Microsoft Team Foundation Server-based source control solution.

Although the team ran into a few issues with the leJOS support libraries, leJOS was used in the final TECHMAN ACV and TCV.

B. DRIVETRAIN DESIGN

The original drivetrain was a simple two-tread design with two wheels per tread (one at the fore and one at the aft). The prototypes used the large regulated motors in a front-wheel drive configuration. Each tread was controlled by one motor; there is no axle that interconnects the left and right sides. The robot steers via differential steering. It can only turn by rotating one tread forward and the other in reverse, thus accomplishing a zero point turn.

The ultimate decision to proceed with a treaded drivetrain instead of a wheeled design was based on the analysis of their respective strengths and weaknesses. Utilization of a wheeled design would have simplified the drivetrain, which would have benefited sustainability and maintainability. Although, the treaded design requires more components and increased complexity, it provided a significantly more stable operating platform. The treads allow for increased points of contact with the terrain, which enables the system to overcome gradients, or obstacles that would destabilize a wheeled design or cause it to get stuck. Additionally, choosing the treaded drivetrain allowed us to take advantage of the leJOS-provided Differential Pilot class. If implemented and trimmed correctly, the Differential Pilot class is capable of sending the robot forward or backward by precise distances and rotating at precise angles. Initial testing with the Differential Pilot class was promising but overall performance was inconsistent due to trim issues stemming from the original tread design.

Robots using the Differential Pilot library need to be “trimmed” in order for the EV3 to perform the calculations necessary for precise movement. This process involved measuring the radius of the wheels for forward and backward movement and the width of the wheelbase for rotations. The library assumes that the robot will be using circular wheels (instead of oval treads) and that the tires are very narrow. The treads are approximately one inch wide, while the smallest tire in the kit has a width of less than 1/16 inch. The team eventually made modifications to the measurements so the devices traveled nearly the correct distance. The adjustment factor is time consuming to find and varies by surface on which the device is driving.

Also causing issues in the original design was a series of design flaws affecting the treads. The structure surrounding the treads was insufficiently rigid as shown in Figure 23. The axles would flex in and bow out while the robot was driving. This made calculating the precise measurements difficult. This also affected the robot's heading, so it would drive at an angle instead of driving straight. Additionally, the treads themselves were not tense enough, which allowed them to slip while driving, resulting in incorrect distance measurements. Due to these flaws, a complete redesign of the drivetrain was necessary to improve the tread effectiveness.

Figure 23. Initial Track Design

The rigidity of the supporting structure was first addressed by reconfiguring the structure in order to reduce the distance between the motor and the tread's drive wheel. Since the axle acts as a class 2 lever, reducing the distance between the drive wheel and the motor also reduced the degree of flex in the axle. Furthermore, the team added a twin set of gears to the tread's supporting structure. The main purpose of the gears was to provide additional tension on the treads by changing the shape of the treads from an ellipse to an obtuse triangle. Additionally, the brackets, which held the gears in place, provided additional mounting points for the supporting structure, which helped increase rigidity. These two changes to the drivetrain yielded significant improvements, which minimized issues, experienced with the original design. Figure 24 shows the redesigned track.

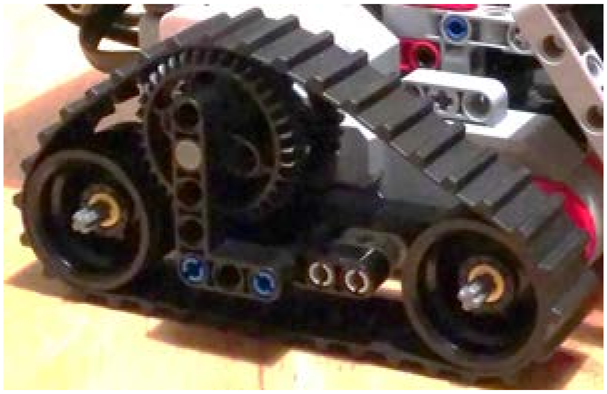

Figure 24. Redesigned Track

C. CLAW DESIGN

The original claw design, shown in Figure 25, was simple and used the medium regulated motor to turn a worm screw that turned a gear connected to an axle. At either end of the axle knob wheels were mounted, which turned matching knob wheels mounted inside the claws. Rotating the worm screw clockwise lowered the claws until they were in their lowest position. Clockwise rotation of the worm screw after the claw is in the lowest position opens the claws. Running the screw in reverse closed and raised the claws. Each claw had three "fingers," with a rubber disk mounted between the top and middle finger to make it easier to grip things.

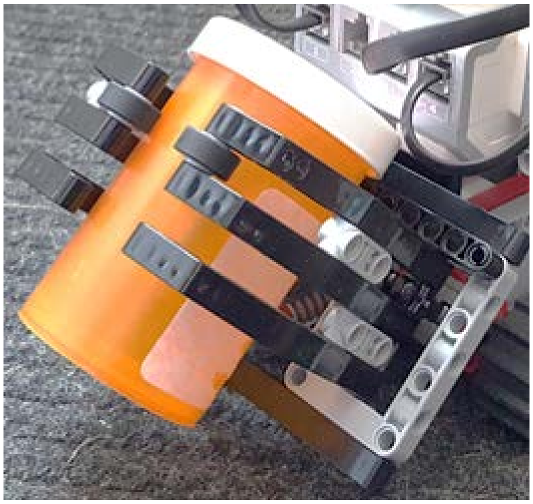

Figure 25. Initial Claw Design

The original design had a few issues. First, the disks helped grip medium sized vials, but some small vials still could not be gripped within the claw. Additionally, by running the motor too far in either direction, the knob wheels could become misaligned (and potentially could break if this was done too often).

Improving the claw required a complete redesign of both the claw itself as well as the gearbox, which transferred power from the motor. The primary objectives for redesigning the claw was to increase the rigidity of the claw structure, improve reliability when attempting to collect different sized objects, and finally avoid the potential of binding or stripping the gearbox.

The first stage of the redesign involved changing the gearbox. Instead of using a worm gear, which is prone to binding when over-torqued, a single bevel gear powered by the motor and connected to a three-stage series of spur gears was implemented. Although this configuration was more complex, the potential of binding gears is significantly reduced by spreading the amount of torque over multiple gears, which can be firmly mounted to the chassis. The redesigned gearbox resulted in a smaller horizontal footprint within the chassis, allowing for optimal placement of the color sensor immediately behind the claw.

When redesigning the claw, improving its rigidity was addressed first. Several iterations were necessary to achieve the correct balance of strength while maintaining full range of motion without obstructing the forward-mounted color sensor. The gripping mechanism was reinforced through the additional supports at the base and tip of the "fingers." The reliability of the gripping mechanism was improved by adding an additional row of fingers to the bottom of the claw as well an additional set of disks to the tip of the fingers. The disks served two purposes in improving the claw's reliability. First, while the claw closes around the intended target, the disks help guide the object into the center of the claw. Second, the rubber on the rollers provides additional friction once the claws have closed, preventing the captured object from slipping out. The final claw design can be seen in Figure 26.

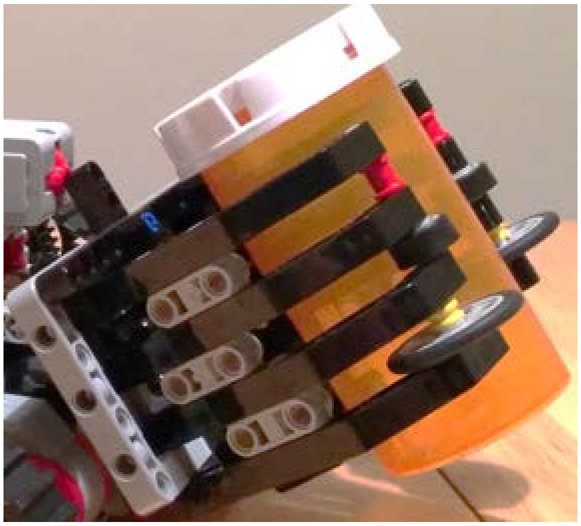

Figure 26. Final Claw Design

D. SENSOR INTEGRATION

Since the hazardous vials were to be a different color than the non-hazardous vials, the team planned on using the forward color sensor, shown in Figure 27, to identify them. Additionally, the team needed some way for the robot to identify the boundaries of the area. The team decided to mark the area on the ground with tape and use a second color sensor to identify the tape as shown in Figure 28. The tape was for convenience with the TCV, but necessary to the ACV to assist in its autonomous dead reckoning.

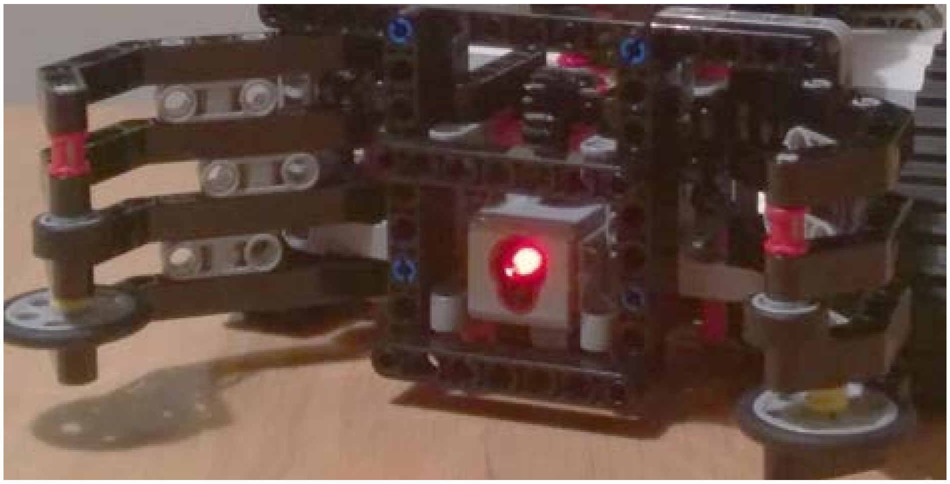

Figure 27. Forward Color Sensor

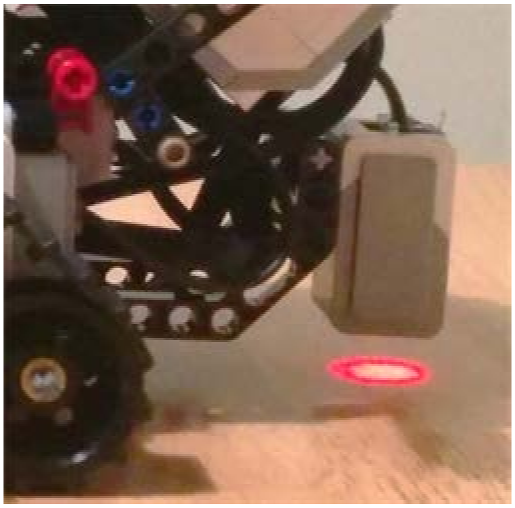

Figure 28. Drag Color Sensor

The touch sensor was used as a safety switch to prevent the claw from being raised too far (see Figure 29). It serves as a mechanical failsafe that protected the claw from retracting too far. The drag color sensor also had failsafe functionality. It could be queried to see if there was a reflected light source within its five-centimeter range. If there was not, it meant that the sensor is more than five centimeters from the ground, presumably because its operator has lifted the robot into the air. The ACV will stop all motors if the operator lifts up the robot.

Figure 29. Touch Sensor

The TECHMAN robots used the ultrasonic sensor, shown in Figure 30, as a rangefinder. The ultrasonic sensor has a theoretical maximum range of 255 centimeters;

however, Bagnall suggest a maximum range of 180 centimeters, with objects beyond that not reliably located. The TECHMAN team's testing found that range to be optimistic as well, and determined that a maximum reliable range is 120 centimeters. The infrared sensor was also an option for range finding. It did not perform as well as the UT sensor as a range finder and was not used in the final design.

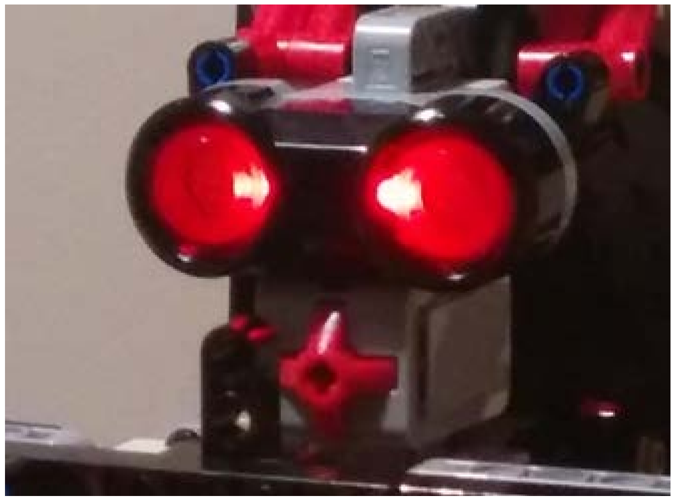

Figure 30. Ultrasonic Sensor

E. SUPPORT KIT

In addition to the robotic device (either the ACV or the TCV), the TECHMAN system includes several other pieces of equipment. The end user is also part of the system, however, creating TECHMAN end user training is outside the scope of our exercise.

The intent was to border the target area on all four sizes with blue painter's tape. The team selected painter's tape because it is readily available in a variety of fairly standardized colors and because it can be put down and picked up without damaging most surfaces. The corral was intended to be a square of red construction paper, eight inches per side. We made it an eight-inch square so we could make it from one sheet of construction paper, and we made it red because the drag sensor would be able to easily distinguish it from blue.

Fabricating an actual carrying case was outside the scope of the project; however, a real project would need a carrying case of some sort. Shaped foam inserts can be custom ordered for a variety of hard plastic carrying cases, which would be necessary for a device made from a kit of detachable plastic parts. This is important because the team discovered that when transported in a shoebox in checked baggage on a commercial airliner, the robot invariably fell apart. If the robot's exterior fuselage was made in a single piece, like it would be on a real system, some of these issues could be mitigated.

The TCV communicates with the operator control unit through a wireless transmission control protocol/Internet protocol (TCP/IP) connection. This means that the fielded configuration for the TCV requires a preconfigured wireless router so the two devices can communicate. This is not necessary for the ACV.

The ACV and TCV were both tested with computer maintenance tools available. The team had the ability to test and troubleshoot issues that arose during testing. Although the end user would not be able to do this, a full system would include depot-level and factory-level troubleshooting tools. To simulate this support, the team had the ability to view advanced logs and make bug fixes during testing.

F. TELEOPERATED SOFTWARE DESIGN

1. TCV State Diagram

The State diagram helps show the different states the TCV would need to pass through to complete a clearing mission. Figure 31 is the state diagram for the TCV. As can be seen in the diagram, the system initializes and connects with the OCU then proceeds to clearing, then ends. Table 14 outlines the state actions and transition events of the TCV state diagram. The table starts with an initial state then details the state actions and transition events that the TCV may experience within that initial state followed by the next state related to the state actions and transition events.

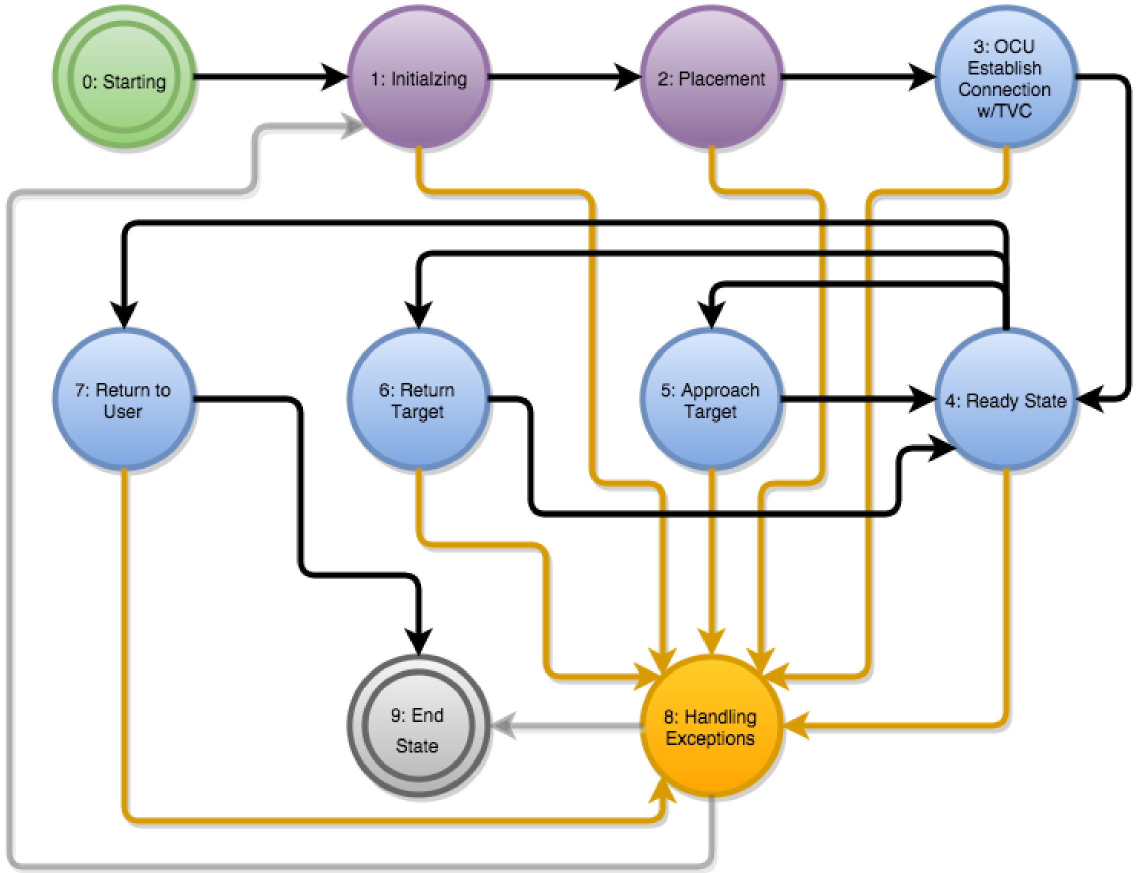

Figure 31. TCV State Diagram

Table 14. TCV State Diagram Actions

State No.	Name	State Actions	Transition Event	Next State
0	Starting	Operator turns on robot. LeJOS boots up.	leJOS Boot complete	1
1	Initializing	Operator starts the TCV/TECHMAN OCU software.	TCV/TECHMAN OCU Software is loaded and ready for user input	2
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	8
2	Placement	Operator places robot in starting location. Robot is placed on ground and oriented to desired direction	Placement Complete	3
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	8
3	OCU Establish	Operator press connect button on OCU	OCU indicates successful connection. (Green)	4

State No.	Name	State Actions	Transition Event	Next State
	Connection w/TCV	Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition. (Red)	8
4	Ready State	Operator directs TCV to move towards target	TCV arrives at target location	5
		TCV closes and raises claws	TCV has captured Vial	6
		TCV closes and raises claws	TCV fails to capture Vial	8
		Area cleared of all vials	TCV has captured all vials	7
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	8
5	Approach Target	TCV stops at target	TCV stopped at target location	4
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	8
6	Return Target	Operator direct TCV to corral	Robot deposits vial in corral	4
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	8
7	Return to User	Robot travels back towards starting location and stops.	Robot is stopped	9
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	8
8	Handling Exceptions	Take appropriate actions to handle exceptions	Error/exception cleared. Robot ready to continue mission	1
		Actions cannot be taken to resolve exception	Mission aborted	9
9	End State	Mission completed or aborted		

Following development of the state diagram, the team developed an INNOSLATE model to help understand the needs of the software to support the TCV. Figure 49 in Appendix A shows the activity diagram developed in INNOSLATE. The model depicts the flow of data as the TCV completes a clearing mission. The model allowed the team to run some different scenarios and have an estimate of the time required to complete a mission. Following the model, the team started developing the TCV software. The model depicts the flow of data as the TCV completes a clearing mission. The model allowed the team to run some different scenarios and have an estimate of the time required to complete a mission. Following the model, the team started developing the TCV software. The model depicts the flow of data as the TCV completes a clearing mission. The model allowed the team to run some different

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2. TCV High-Level Design

The OCU command and control software resides on the OCU. The software allows form automatic robot discovery over the network, automatic sensor initialization, and automatic positioning of the claw. The software provides the operator with control of the robot, motor speed control, and provides continuous sensor feedback and visualization. Figure 32 shows a visual representation of the OCU software's data exchange with the operator.

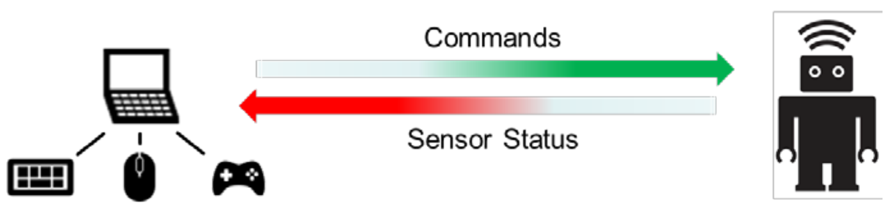

Figure 32. OCU Software Data Exchange

The TCV OCU software utilizes a two-layered modular architecture designed to optimize for reuse of existing application programing interface (API)s and functions with minimal complexity. The first layer is the user interface, which displays relevant information to the operator as well as allows commands to be sent to the TCV. The user interface is coupled to the functional component layer, which is a series of software modules responsible for processing exchange of user inputs and TCV outputs. The OCU software itself runs entirely on the field laptop and requires no additional code software to be loaded onto the TCV beyond the base leJOS operating system. This is achieved through the implementation of existing leJOS APIs and functions that are provided as part of the leJOS software development kit. This approach reduced complexity by

limiting the software footprint and potential points of failure. The OCU issues commands and receives sensor data using TCP/IP over a standard wireless network connection.

G. AUTONOMOUS SOFTWARE DESIGN

1. ACV State Diagram

As with the TCV, the State diagram helps show the different states the ACV would need to pass through to complete a clearing mission. Figure 33 shows the state diagram for the ACV. As can be seen in the diagram, the system initializes then proceeds to clearing mission and finally ends. Table 15 outlines the state actions and transition events of the ACV state diagram. The table starts with an initial state then tracks to the state actions and transition events that the ACV may experience within that initial state followed by the next state related to the state actions and transition events.

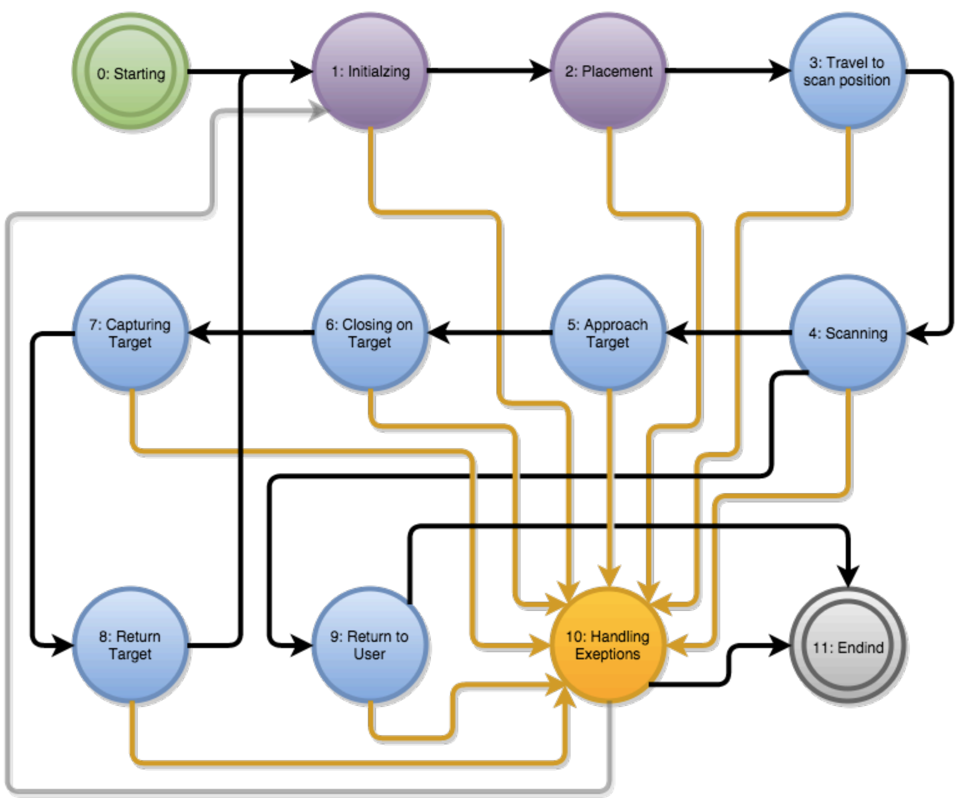

Figure 33. ACV State Diagram

Table 15. ACV State Diagram Actions

State No.	Name	State Actions	Transition Event	Next State
0	Starting	Operator turns on robot. leJOS boots up.	leJOS Boot complete	1
1	Initializing	Operator starts the ACV/TECHMAN software.	ACV/Tuchman Software is loaded and ready for user input	2
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
2	Placement	Operator places robot in starting location. Robot is placed on ground and oriented to desired direction	Placement Complete	3
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
3	Travel to scan position	Operator gives start command. Robot travels to scan position.	Robot reaches scan position	4
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
4	Scanning	Robot rotates 90 deg. CCW and begins scanning in 2 deg. Increments until it identifies a target.	Azimuth oriented towards center of identified target.	5
		Robot rotates 90 deg. CCW and begins scanning in 2 degree increments until it rotates 360 deg. Without identifying a target	Scan complete. Rotate 90 Deg. CW to orient towards starting point	9
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
5	Approach Target	Robot approaches target at full speed until half the distance to the target is traversed. Claws open and are lowered.	Robot has reached half the distance to target. Claw is lowered and open.	6
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
6	Closing on Target	Robot approaches the target at half speed. Robot travels remainder distance plus 2 distance units.	Robot has reached target and displaced target two distance units	7
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
7	Capturing Target	Robot captures target by closing then raising the claw. Robot orients back towards corral	Target captured and robot oriented for return.	8
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10

State No.	Name	State Actions	Transition Event	Next State
8	Return Target	Robot travels back towards starting location. Robot opens claws and back away from dropped off vial and stops	Robot is stopped and claws are open	1
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
9	Return to User	Robot travels back towards starting location and stops.	Robot is stopped	11
		Unexpected condition detected. Robot sends error code or fails to initiate desired state.	Appropriate action taken to handle condition.	10
10	Handling Exceptions	Take appropriate actions to handle exceptions	Error/exception cleared. Robot ready to continue mission	1
		Actions cannot be taken to resolve exception	Mission aborted	11
11	End State	Mission completed or aborted		

After developing the ACV state diagram the developers sought to understand the operational concept as it relates to the ACV. Figure 34 shows a pictorial representation of the ACV operational concept. The concept shows the ACV search area, the allowed ultrasonic sensor range, start point, scan point, vials to be cleared, and the clearing path for a vial. The concept along with the state diagram gave the developers a visual aid to help with software development.

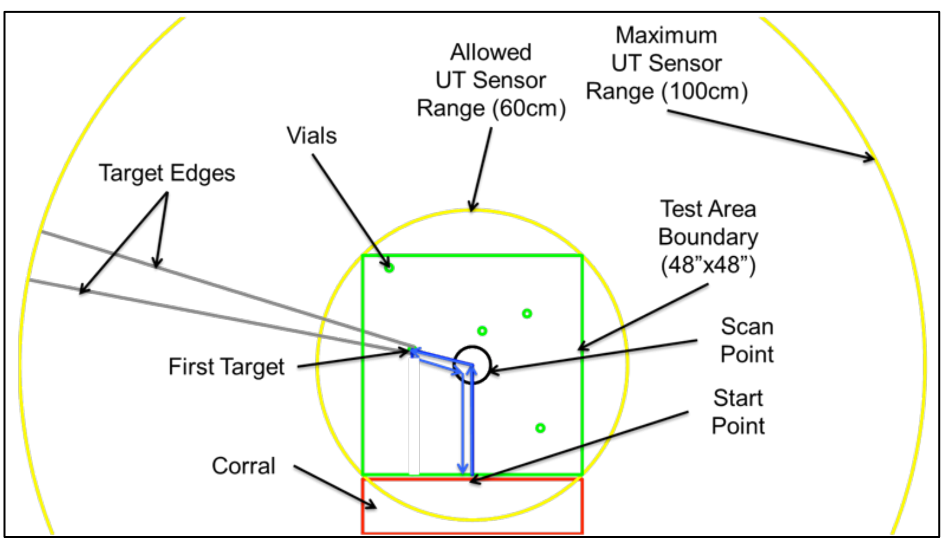

Figure 34. ACV Operational Concept

2. High-Level Design

The TECHMAN ACV uses a three-layer software architecture. The software at each layer is provided by a different organization. The LEGO Group provides the EV3 layer software, the leJOS project provides the leJOS layer, and Project TECHMAN developed the TECHMAN layer. Software at a higher level can access the functionality provided by lower layers through an application programming interface, but lower layers do not reach into higher ones. Figure 35 shows the three-layer software architecture.

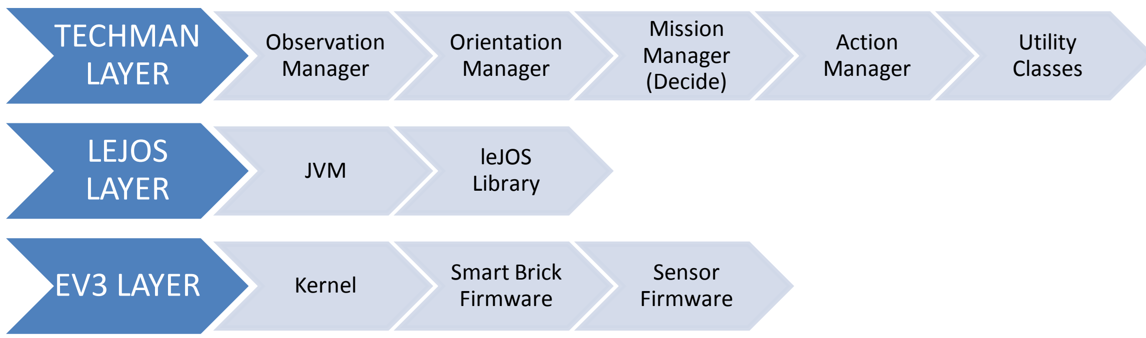

Figure 35. TECHMAN Three-Layer Software Architecture

Within the TECHMAN layer, the different parts of the program are divided into packages, which serves as a secondary layering scheme. The Mission Manager can reach to its “right” and order the robot to take actions (including moving the robot, raising or lowering the claw, and causing the EV3 to beep) by calling methods from the Action Manager, or it can reach to its “left” and retrieve information about the robot’s state (including current sensor readings and the memory of past sensor readings) from the Orientation Manager. The Orientation Manager exposes a method to obtain a new set of current sensor readings from the Observation Manager, which can be called on demand by the Mission Manager. The layers are designed to mimic Col. John Boyd’s OODA loop, which models human decision-making. Under OODA theory, the decision maker *observes* something, *orients* themselves to what they saw using their training and experience, *decides* what action to take, and *acts* in accordance with their decision.

The “business logic” of the robot’s code is contained in the Mission Manager, which implements Boyd’s Decision step. The other classes can be seen as supporting the Mission Manager. The ACV supports loading five missions simultaneously, although only one can be executed at a time.

The TECHMAN ACV prototype, as tested, has five missions loaded, “*FourByFour*,” and four diagnostic missions. In *FourByFour*, the ACV drives to the center to do a 360-degree scan. In two diagnostic missions, the robot drives a set distance at full and half speed, respectively. In the other two diagnostic missions, the robot rotates a set distance. The diagnostic missions are intended to be used in finding the robot’s “trim values,” that is, the adjustments needed to be made between ACV-measured “distance units” and real life distance traveled. They were also useful for testing the capabilities of the device during some of our formal testing.

3. The Observe and Orient Layers

The Observe and Orient layers have high cohesion between them, which enables them to work well together. Roughly speaking, the Observe layer is responsible for polling the current state of the sensors and the Orient layer is responsible for keeping track of the ACV’s state. For example, consider the question of whether the robot is within the target area. Through the Observation Manager, the drag color sensor can be queried to see if the device is currently driving past the blue line that denotes the end of the target area. The Orientation Manager tracks the number of times the robot has crossed a blue line. Since the robot starts outside the box, if the number of line crossings is even, the robot is outside the box (because it crossed into the box, then crossed back out). If the number of line crossings is odd, the robot is inside the box (because it has not crossed out of the box since the last time it entered). The Orientation Manager can be queried on whether the device is in the target area based on this information.

Most methods within the Orientation Manager are very specific to the algorithms used by the ACV. In addition to the target area querying described above, when the robot is locked on, the Orientation Manager tracks the number of hits on the current target. This

is for use in the target detection algorithm. The ACV should be pointed at the middle of the target when it drives up and grabs the vial. To do this, the program makes sure the device finds the “near” edge of the vial, then makes very small turns (approximately two degrees in the current setting) until it can no longer see the “far” edge. It then uses the number of scans and the angle of the turns to calculate the wedge during which the target was visible. The device then turns back to the center of that wedge so it can approach the target.

The Observation Manager and Orientation Manager communicate through a data structure called the Sensor Reading, which stores readings for all four sensors in a single object. Sensor Reading objects are passed to the Orientation Manager, which can use simple queries to retrieve the data.

Early versions of the ACV would have the Orientation Manager save multiple objects and do calculations on several Sensor Readings at a time. However, this eventually became too complex. The team decided to simplify the Orientation Manager and store only the information that was immediately mission relevant. For example, more recent versions of the ACV do not store every color reported by the drag sensor. Instead, there is a counter that indicates whether the device is in the target area.

4. The Action Layer

The Action Manager controls the physical hardware of the ACV. It can be divided into three major sections, the drivetrain, the end effector, and the smart brick. The Action Manager is implemented as a series of static methods, each of which result in the robot creating a specific “output” such as driving forward, lowering the claw, or generating sounds using the buzzer. The actions in the Action Manager are stateless. They are compatible with being called in any order while the device is running.

The easiest part of the action manager to understand is the end effector controls, which are used to raise and lower the claw. Specifically, there is one method to raise the claw all the way and a second method to lower the claw all the way. Grasping the claw shut is the first part of raising the claw, and opening the claw is the last part of lowering

it. Due to the hardware modifications made to the device's claw, attempting to raise a claw already in the top position or attempting to lower a claw in the lowered position will not harm the robot. Logically, it is the response of the Mission Manager and Orientation Manager to track the claw's state.

The next functions of the Action Manager are the actions related to the buzzer and the lights on the smart brick. These functions could be used to send visual or auditory output to the user. These functions are thin wrappers around functions provided by the leJOS environment, which in turn wrap functions provided by the hardware. The final functions of the Action Manager are the drivetrain methods, which wrap functions provided by the leJOS Differential Pilot class in the same way.

5. The Mission Layer

The Orientation Manager is a representation of the device's state, and the Action Manager is a representation of the potential actions the robot can take. The link between "When the device is in state X, take action Y" is located in the Mission Manager.

A different Mission Manager represents each of the potential sets of instructions the ACV can take. At startup, the user selects the Mission Manager they would like to control the robot for that mission.

The Mission Layer fulfills Boyd's "decide" step. The team decided to call it "Mission" rather than "Decide" because it implicitly tracks a different kind of state than the Orientation Manager does. The Orientation Manager tracks the state of the device relative to its physical environment. The Mission Manager tracks the specific instructions given to the device (in other words, the mission), pending instructions, and estimated instruction completion time.

There are three functional missions, which the ACV is programmed to execute, as well as two for debugging purposes. The three functional missions send the ACV into the target area, have it drive to the scan point (a specific distance from the start point), and have it rotate while scanning until it finds a target. The ACV then approaches the target, grabs it, returns to the scan point, and then returns to the start point.

The *FourByFour* mission starts from the middle of the target area and scans 360 degrees. The *LeftCorner and RightCorner* missions start from a corner of the target area and scans 90 degrees.

The debugging missions have the robot drive a set distance and rotate a set distance, respectively. These are used for calibrating the Differential Pilot Adapter.

An action diagram depicting the *FourByFour* mission is shown in Figure 50, Figure 51, and Figure 52 of Appendix B.

6. The Support Classes

In addition to the four architectural layers, there are also several support classes. Support classes are accessible from most places in the code and are designed for things that do not fit into the OODA framework. For example, the startup code and the SlightlySmarterMenu class are support classes. The SlightlySmarterMenu class runs on startup and waits for user input. It is named that because it uses TECHMAN-designed wrappers around the input button functionality in leJOS. In several places, leJOS uses "numerical" enums for things that are not logically numbered, such as which button is pressed.

The other primary support class is the logging functionality. The Logger has functionality designed to show or hide messages when the program is run at different levels. For example, at the most restrictive priority level, RUNNING, only messages marked "RUNNING" are displayed to the user. Each instruction to create a log entry is assigned a priority when the code is written, and the log priority level can be set to different values in different areas of the code. For example, when debugging an issue with the Mission Manager, if all the other areas of the code are set to RUNNING, but the Mission Manager logging is set to DEBUG, all messages except the Mission Manager messages will be suppressed. This aids in debugging.

H. OPERATION

1. Mission Preparation

Mission preparation begins with designation of an area to be cleared. Once identified, the area must be cordoned off using the included blue painter's tape and measuring tape. The cordoned off area must be a four foot by four foot square. After the area has been prepared, execution of the clearance mission will proceed in accordance with either the teleoperated or autonomous vehicle operation instructions. The following sections 2 and 3 outline operational instructions for the UGVs.

2. Teleoperated Operation

Once ready for operations, unpack the robot from the transport case. Install charged batteries into the EV3 brick. Next, power on the field laptop followed by the included wireless access point. Once the field laptop has finished starting up, the user must launch the TCV OCU software and confirm the laptop has connected to the wireless access point. Finally, turn on the robot by pressing the power button. The robot will automatically connect to the wireless access point once it has finished powering up.

The TCV OCU software, displayed in Figure 36, allows for control of the robot and visualization of sensor data once a connection is established. Pressing the OCU software's connect button will begin the automated connection and initialization process. Once the connection process has begun, the robot will emit a series of beeps to indicate the OCU has successfully connected and initialized the robot. The system is ready for operation once the robot emits three consecutive beeps. In addition to movement and claw control, the OCU software allows for adjustments to the turning and driving speed of the robot as well as individual trim of the left and right drive motors for calibration. The OCU software also provides feedback from the robot's color, distance, and touch sensors.

Finally, before proceeding with its mission, the robot must be placed at the edge of the area to be cleared. Drive the system into the target area, grab a vial, and bring it

back to the corral. Continue this until all the vials are cleared. When the mission is complete shut down the system, remove the batteries, and place in transport container.

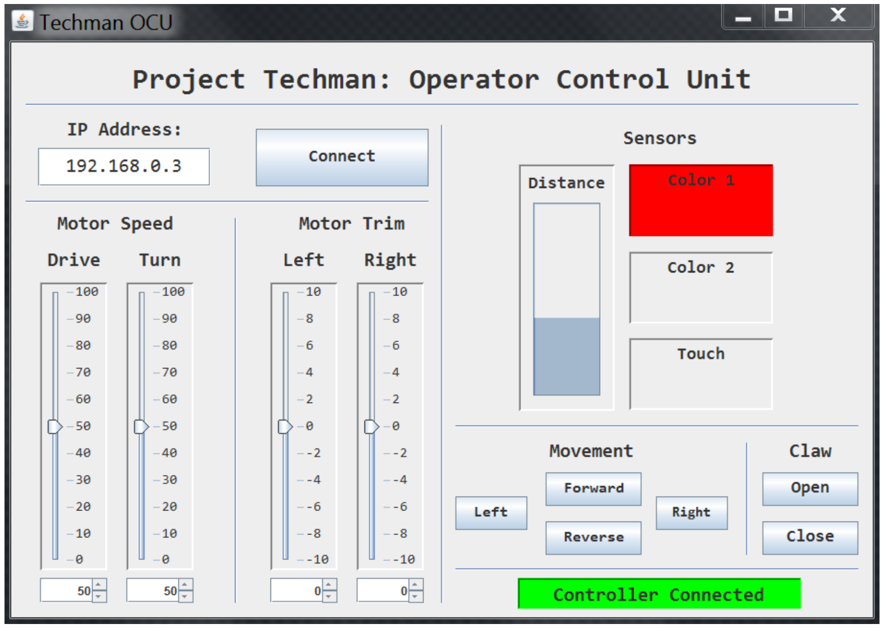

Figure 36. TCV OCU Software Graphical User Interface

3. Autonomous Operation

Once ready for operations unpack the robot from the transport case. Install charged batteries into the EV3 brick. Turn on the robot by pressing the power button.

Once the device is running, select the commands to run the program OODA_Loop.jar. Once the program is running, select the *FourByFour* mission using the button in the center of the keypad.

Place the device on the edge of the area to be cleared. The device will drive into the target area, grab the vial, and bring it back to its start point, and then the program will end. If there are multiple vials, run the OODA_Loop.jar program once for each vial. Once all the vials are cleared, remove the batteries and place in transport container.

VI. TEST AND EVALUATION

A. MEASURES OF EFFECTIVENESS

Measures of effectiveness (MOE) and measures of performance (MOP) were used to determine how well the TECHMAN ACV and TCV solved the customer’s problem and how well each UGV component performed in doing so.

> MOEs were used to measure the effect (mission accomplishment) that came from the use of the system in its expected environment. That environment included the system under test and all interrelated systems, that is, the planned or expected environment in terms of sensors, command and control, and platforms, as appropriate, needed to accomplish an end-to-end mission. (DAU 2012)

> MOPs are system-particular performance parameters such as speed, payload, range, time-on-station, frequency, or other distinctly quantifiable performance features. (DAU 2012)

Table 17 contains the MOEs for the TECHMAN family of vehicles (FOV).

B. TEST PLAN

Testing was performed at Aberdeen Proving Ground, MD from 5 September through 7 September 2015. The TECHMAN team provided the facilities, instrumentation, test support equipment, and personnel required to perform testing. All test data and the test team recorded incidents. A summary of the test objectives is presented in Table 16.

Table 16. Subtests and Objectives

Subtest	Objective
Physical Characteristics	Determined the physical dimensions, weight, and center of gravity measurements for the TECHMAN (FOV)
Performance Characteristics	Determined whether the system performance characteristics of the TECHMAN FOV met the requirements
Standard Nominal Clearing Test	Determined the capability of the TECHMAN FOV to clear a standard test area.
Non-Standard Clearing Test	Determined the capability of the TECHMAN FOV to clear a Non-Standard test area.

Table 17 shows the Data Source Matrix for the TECHMAN FOV. The table links the requirements with the MOEs and test events.

Table 17. TECHMAN Family of Vehicles Data Source Matrix

Operational Task	Req #	Requirement		MOE	Physical Characteristics	Performance Characteristics	Standard Nominal Clearing Test	Non-Standard Clearing Test
Operational Task 1: The Robot shall pass and receive mission information	KSA 1	The robot shall notify the operator of system malfunctions.	T=O	System malfunctions will be recorded. Notifications of malfunctions from the system will be noted. The actual malfunctions and notifications of those will be compared to check effectiveness		X	X	X
	KSA 2	The robot shall store a mission log file for retrieval by the operator.	T=O	Log files will be downloaded and checked for correctness		X	X	X
	KSA 3	When returning a vial to the corral, the robot shall play a distinct sound for a “hazardous vial” and a different sound for an inert vial.	T=O	Operators will check vials that have been returned			X	X
Operational Task 2: The Robot shall operate in its intended environment	KPP 1 - Energy	Starting with fully charged batteries, the robot shall run for the specified amount of time without swapping batteries.	T: 2 hours, O: 3 hours	Operator will run robot until batteries are no longer able to power the robot. The time will be recorded		X		
	KPP 2 - Transport	The system shall be transportable in the specified number of containers; each container shall be transportable by a single Solder.	T: Two containers, with the weight of each container not to	System weight and dimensions will be checked and recorded		X		

Operational Task	Req #	Requirement		MOE	Physical Characteristics	Performance Characteristics	Standard Nominal Clearing Test	Non-Standard Clearing Test
			exceed 35 lbs. O: One container, with a weight not to exceed 35 lbs.					
	KSA 4	6 AA batteries or rechargeable equivalent shall power the robot.	T=O	Batteries will be checked	X			
	KSA 5	The system shall operate in a manner safe to its operators.	T=O	Any unsafe operations or actions will be recorded	X	X	X	X
	APA 1	Batteries shall be replaceable within two minutes.	T=O	Operator will check for replacement time	X			
	APA 2	The system shall comply with the FCC's requirements for a Class D device. Harmful interference, as defined in the FCC rules, shall not prevent the system from accomplishing the mission.	T=O	System certificates will be checked for compliance	X			
	APA 3	The system shall be operated by not more than one servicemember	T=O	Operation by a single operator will be checked			X	X
Operational Task 3: The Robot shall propel itself under its own power, including while carrying vials	KSA 6	The robot shall traverse terrain of smooth concrete or blacktop surfaces	T: Concrete or blacktop with coefficient of friction between 0.2 - 0.9 O: Gravel or forest floor	The system will be checked for ability to traverse terrain. Any limitations will be recorded		X	X	X
	KSA 7	The robot shall be able to change its heading to any 360 degree orientation	T=O	Maneuverability will be check and any limitations will be recorded		X	X	X
Operational Task 4: The Robot shall clear a given area of radiological threats	KPP 3 – Clearing Area	The robot shall clear a rectangular area (the "target area") of a defined size.	T: 16 square feet O: 625 square feet	Ability to clear the entire target area of vials will be checked			X	X
	KPP 4 – Vial Transport	The robot shall secure all vials and return them to the corral for disposal by trained personnel and a separate system at the required rate.	T: P(return standard size vial) = 95% O: P(return standard size vial) =	Ability of the robot to transport vials to the corral will be checked			X	X

Operational Task	Req #	Requirement		MOE	Physical Characteristics	Performance Characteristics	Standard Nominal Clearing Test	Non-Standard Clearing Test
			99%					
	KSA 8	The robot shall distinguish a “hazardous” colored vial from vials of other colors with a specific probability of distinction.	T: P(distinction): 90% O: P(distinction): 95%	Operators will check vials that have been returned and record results		X	X	X
	KSA 9	The system shall detect vials under fluorescent lighting conditions (between 2000 and 900 lumens).	T=O	System operation will be check and any limitation will be recorded		X	X	X
	KSA 10	A continuous blue marking not less than 1 inch thick shall surround the target area.	T=O				X	X
	KSA 11	The start and end point for the robot shall be a 12” by 48” red colored tile called the corral. The corral shall be located at the edge of the target area.	T=O	Test course will be checked for proper layout			X	X
	KSA 12	The system shall have the specified probability of completing a 2 mission hours without an essential function failure.	T: 0.75 Probability of completing a 2 hour mission without an essential function failure O: 0.9 Probability of completing a 2 hour mission without an essential function failure	Any anomalies during testing will be recorded and used to determine the reliability. All test events will be time stamped from start to stop and the time of anomalies will be recorded		X	X	X

Operational Task	Req #	Requirement		MOE	Physical Characteristics	Performance Characteristics	Standard Nominal Clearing Test	Non-Standard Clearing Test
	KSA 13	The system shall have the specified probability of completing 2 mission hours without a system abort	T: 0.95 probability of completing a 2 hour mission without a system abort O: 0.99 probability of completing a 2 hour mission without a system abort	Any anomalies during testing will be recorded and used to determine the reliability. All test events will be time stamped from start to stop and the time of anomalies will be recorded		X	X	X
	APA 4	The system shall not exceed the specified MMH/OH ratio	T: 0.04 MMH/OH O: 0.015 MMH/OH	Any anomalies during testing will be recorded and used to determine the reliability. All test events will be time stamped from start to stop and the time of anomalies will be recorded		X	X	X
	APA 5	The system shall pass the Standard Nominal Test Pattern according to the threshold and objective values defined by that test pattern.	T: See the SNTP O: See the SNTP	The system will be checked for the ability to complete the SNTP in 15 minutes or less			X	

1. Physical Characteristics

a. Objective

- Measured the physical dimensions (length, width, height, etc.), weight, and center of gravity measurements of the TECHMAN ACV and TCV.
- Determined whether the TECHMAN FOV exhibits good human engineering design characteristics.

b. Criteria and Data Analysis

- The results of the physical dimensions, weight, and center of gravity measurements of the TECHMAN ACV and TCV were used to determine the transportability of the TECHMAN FOV. The measurements also provided input to the safety analysis and ability of the 5th to 95th servicemember to operate the systems. This portion of the physical characteristics provided input to evaluation of:
    - KPP 2
    - KSA 5

- The results of the general design fit and finish and battery placement of the TECHMAN ACV and TCV were used to determine time required for battery replacement and number of batteries. This portion of the physical characteristics provided input to evaluation of:
  - KSA 4
  - APA 1

- The results of the human engineering design characteristics were used to determine ease of use of the controls, displays, and labeling. This portion of the physical characteristics provided input to the evaluation of:
    - KSA 1
    - KSA 5

c. Test Procedures and Data Required

- Physical Dimensions – Physical dimensions of the TECHMAN ACV and TCV were measured using steel tapes, levels, and calipers while the system is positioned on a hard level surface.
- Weight – The TECHMAN ACV and TCV weight was measured with batteries installed and all mission essential equipment attached. The weight of the system was measured using a calibrated digital scale.

- Rollover Threshold – Rollover Threshold was measured by placing the TECHMAN ACV and TCV on a flat surface with an inclinometer attached. The flat surface was raised until a load shift occurred. The ACV and TCV were tilted about their roll axis. Testers insured the system was being caught once the rollover threshold has been reached.
- Design – The TECHMAN ACV and TCV was timed for depleted battery removal and charged battery install. Any noteworthy design issues were recorded.
- Controls, Displays, and Labeling – All controls, displays, and labeling were inspected with respect to human factors engineering (HFE).

The following data were recorded:

- physical dimensions
- weight
- rollover threshold
- design and battery system
- human factors engineering measurements
- photographs

d. Physical Characteristics Results

Figure 37 shows the RCV on the scale being used to obtain weight measurements. Figure 38 and Figure 39 show two views of the rollover and slip angle apparatus. The board was raised until the robot either tipped or slipped. The coefficient of friction between the robots and wood is approximately 0.7 to 1.0. The results of the physical characteristics testing can be seen in Table 18. With regards to slip angle and rollover angle, the robots would slip before the rollover threshold occurred except when the robot rear was facing down slope. Both the ACV and TCV would tip before slipping in this orientation. However, once the tip occurs the robots would rest against the rear color sensor, which prevented the robots from completely rolling over.

Table 18. Physical Characteristics

Parameter	ACV	TCV
Length (inches)	11	10.5
Width (inches)	6.25	6.25
Height (inches)	6.625	6.125
Weight (pounds)	6.07	6.06
Rollover Left (degrees)	46	46
Rollover Right (degrees)	45	44
Rollover Front (degrees)	43	42
Rollover Rear (degrees)	19	19
Slip Angle Left (degrees)	27	25
Slip Angle Right (degrees)	28	28
Slip Angle Front (degrees)	28	30
Slip Angle Rear (degrees)	NA	NA

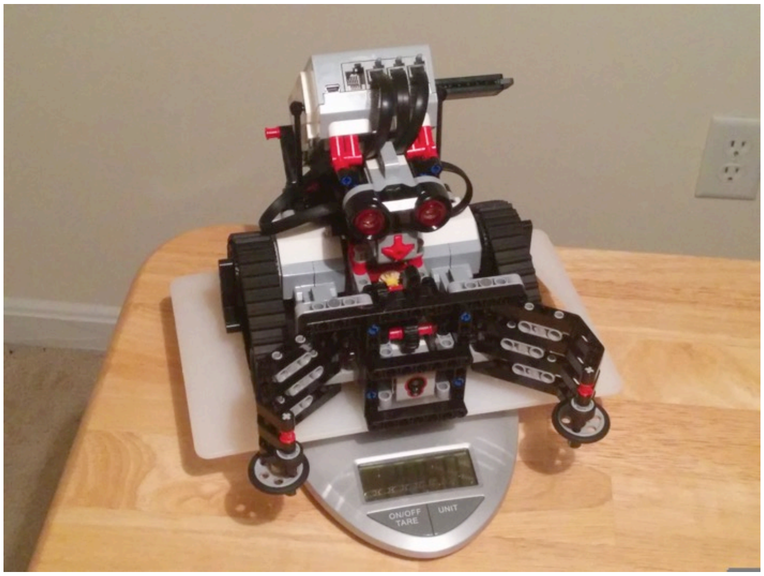

Figure 37. RCV on Scale

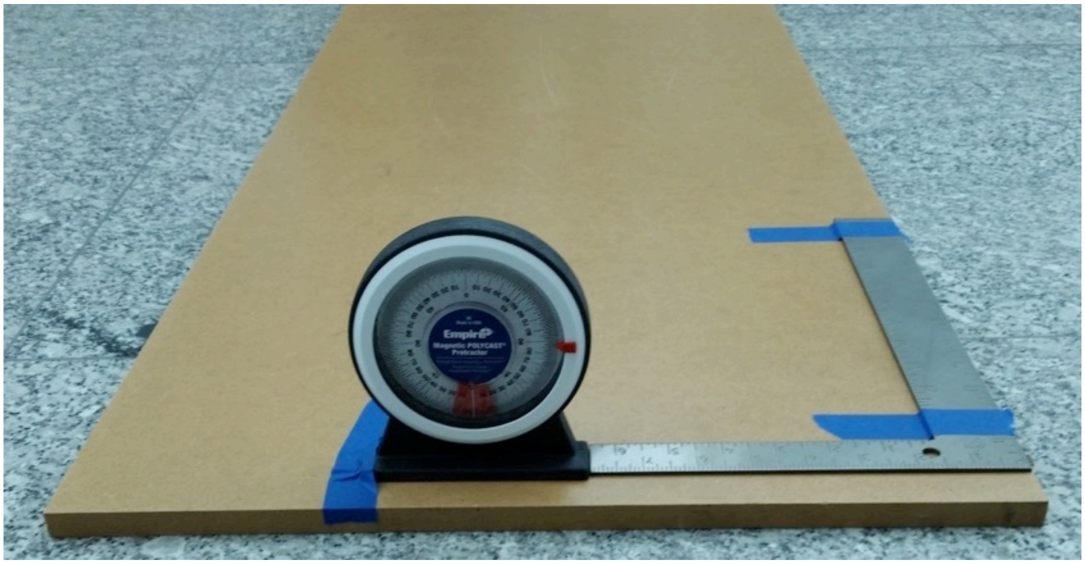

Figure 38. Rollover Threshold Test Apparatus View 1

Figure 39. Rollover Threshold Test Apparatus View 2

The operators were able to change the six rechargeable batteries within two minutes.

The robots have pinch points around the claw and tracks. However, no pinch points have the capability of causing serious injury. No other adverse HFE issues were found with the systems. Figure 40 shows characteristic photos of the robot.

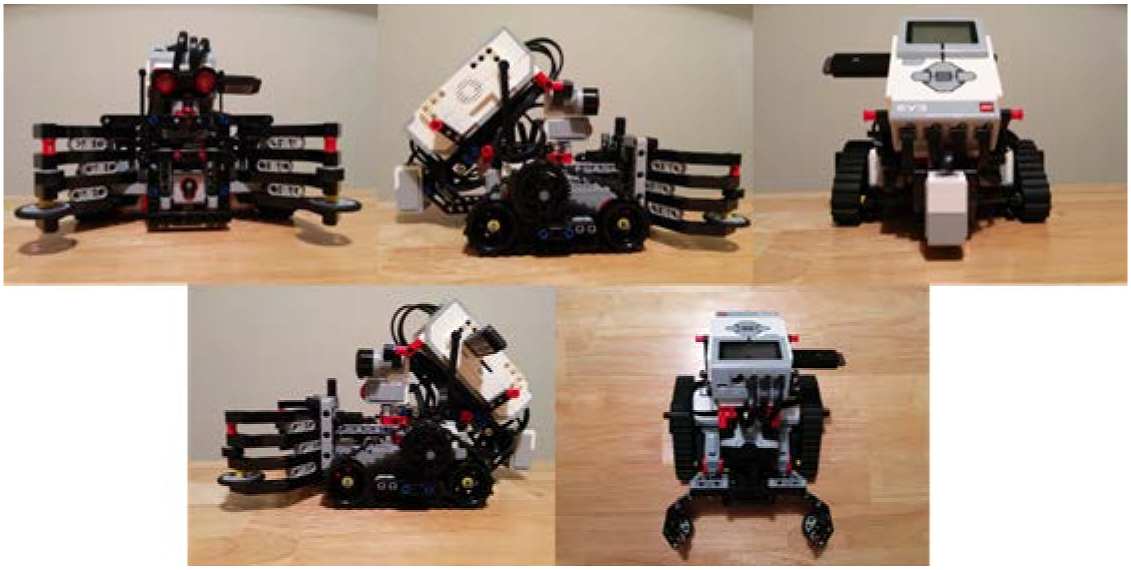

Figure 40. Different Views of the TECHMAN UGV

2. Performance Characteristics

a. Objective

- Determined whether the TECHMAN FOV performance characteristics met the requirements of the TECHMAN CDD.

b. Criteria and Data Analysis

The results of the performance characteristics were used to determine the performance and safety of the TECHMAN ACV and TCV. The performance characteristics provided input to evaluation of:

- KSA 1–3
- KPP 1
- KSA 5
- KSA 6–9
- KPP 4
- APA 3

c. Test Procedures and Data Required

- Top Speed – The top speed of the TECHMAN FOV were determined by recording the time it took for the system to travel 20 feet in both the forward direction and reverse direction. The test was performed with batteries with at least 90% charge. The test took place on representative smooth concrete.
- Turning ability (Differential Piloting) – The ability of the TECHMAN FOV to change its heading to any 360-degree orientation was determined by using the systems differential piloting on representative smooth concrete. The test team recorded the amount of time required to turn 180 degrees and 360 degrees. The ACV was checked for its ability to maintain awareness of the degrees turned. The system tracks and driveline were inspected for any issues or wear.
- Terrain – The ability of the TECHMAN FOV to cross smooth concrete tile and carpet was determined maneuvering the system in a figure eight pattern on representative concrete. Subjective observations were made by the test team of the system's ability to traverse the terrain. The system tracks and driveline were inspected for any issues or wear.
- Sensor Systems – The TECHMAN FOV sensor systems functionality was determined by checking for proper operation. These tests proved operation of the sensor itself, mounting position, and ability of the software to recognize and interpret sensor input. Three different sensors where tested:
  - Color – The color sensor's abilities were determined by checking the ability to find the blue marking one inch wide and one foot long on the representative concrete. The color sensors ability was also determined by checking the ability to distinguish between a hazardous vial (green) and non-hazardous vial (gray). The color sensors ability was tested under fluorescent lighting.
  - Ultra-sonic – The ultra-sonic sensor's ability was determined by placing a vial in front of the system and moving TECHMAN until system notified the operator a vial is in sight. This test was performed

putting the vial at the extremes of the advertised sight cone of the sensor. Once sighted the vial distance from the sensor and degrees off the centerline of the sensor were recorded.

    - Touch Sensor – The ability of the touch sensor was determined by raising the vial lift arms until the sensor was depressed and indicated to the system that the arms were lifted.

- Operational Time – The operational time of the TECHMAN FOV was determined by recording the amount of time the system operated starting with fully charged batteries. The system was driven while performing various operational tasks for two hours. The system operational time test was performed on smooth concrete.
- System Autonomy (ACV) – The autonomous ability of the TECHMAN ACV was determined by having the system start at a blue marking one inch wide and one foot long then maneuvering on its own to another blue marking four feet away, turning 180 degrees and returning to the starting location. The system autonomy test was performed on smooth concrete.
- Locating, Lifting, Transporting Vials – The ability of the TECHMAN FOV to locate, lift, and transporting was determined by placing the various sized vials four feet in front of the system. The system would maneuver to the vial and lift the vial then return to its starting location. The testers checked for the secureness of the vial while in the lift arms.

The following data were recorded:

- time to travel 20 feet (forward / reverse)
- time to turn (Differential Piloting)
- ability to cross terrain
- ability to detect marking line
- ability to distinguish vials
- functionality of lift arm sensor
- ability of lift arm

- operational time with fully charged batteries
- ability of the ACV to start maneuver and return to the same location
- any issues or faults with the system
- photographs

d. Performance Characteristics Results

Figure 41 shows the test setup to test the time to travel 20 feet. The ACV and TCV at 100% power completed the 20-foot distance in 29 seconds. Reverse speed of the systems in the same. The operator can adjust the speed of the TCV, the test was ran at 50% speed setting, which allowed the TCV to complete the 20-foot distance in 56 seconds.

Figure 41. 20-Foot Travel Test

Both the ACV and TCV were able to change their heading to any 360° orientation. Both also had nearly identical time to perform a zero radius turn. A 180° turn took approximately one second and 360° turn took approximately two seconds. The TCV and ACV also proved its ability to traverse concrete, tile, wood, and carpet with any adverse effects by driving in a figure eight pattern. No adverse wear was observed on the tracks or drive motors.

While both the ACV and TCV have color sensors mounted with the intended ability to detect a marking line and distinguish vials, neither system was mature enough to use those sensors. Because of this, neither system was able to detect a marking line or distinguish vials. Future systems may gain this capability but the current systems do not and therefore do not meet the CDD requirement as written.

The lift arm and claw system were tested with small and large vials. As long as the vials are within the robots open claw the UGVs have no trouble picking up the vials. The lift arm sensor functioned as intended and the vials were held securely within the claws. The ACV system is able to successfully locate and retrieve a vial placed four feet in front of the claw.

Starting with fully charged batteries, both the ACV and TCV were able to perform various mission tasks for two hours without changing batteries

The ACV marginally passed the autonomous ability test. The system was able to travel out a distance, turn around and return to nearly the same spot. However, the system routinely was a few inches off from the start point. This is likely due to the trimming of the robot. Fine tuning the trimming to the floor surface improved the ACV’s ability to return to the original starting point.

When performing the vial location test for the ACV the system was not able to find the vial. The test team tried many different methods to try and determine the problem. The test team finally determined that the ultrasonic sensor had malfunctioned and was not providing the system with proper readings. A properly functioning sensor was added to the system, which corrected the issue. The problem was not observed again during testing.

3. Standard Nominal Clearing Test

a. Objective

- The objective the standard nominal clearing test (SNCT) is to give a base line test that was used to compare the performance and reliability of the TECHMAN ACV and TCV. The SNCT is based off of a representative mission

b. Criteria and Data Analysis

- The results of the SNCT were used to determine the performance, reliability, and safety of the TECHMAN ACV and TCV. The SNCT provided input to evaluation of:
    - KPP 3–4
    - KSA 1–3
    - KSA 5
    - KSA 6–13
    - APA 3–5

c. Test Procedures and Data Required

Figure 42 shows the 16 square foot test area for the SNCT. The vials were placed in a specific pattern. The TECHMAN ACV and TCV ran through the SNCT four times each. The systems proceed from the corral area to find and retrieve the vials and return the vials to the corral area. Time to clear the area was recorded, number of vials returned, system identification of the vials (correct or incorrect), number of battery swaps required, and any system failures or anomalies.

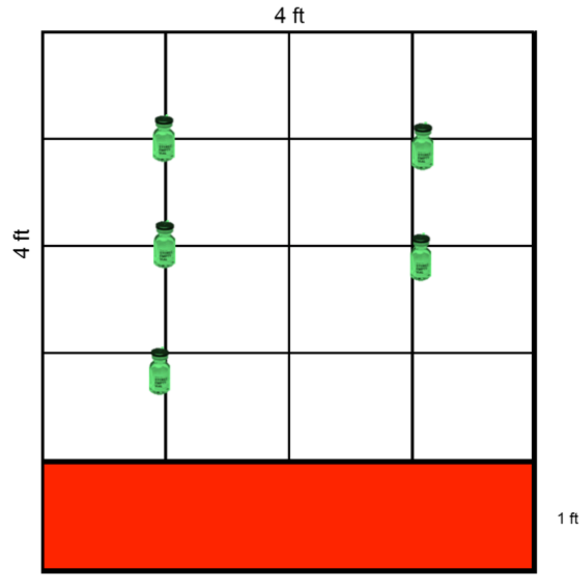

Figure 42. SNCT Vial Configuration

The following data was recorded:

- overall time to clear area
- time per vial
- average time per vial
- number of vials returned
- number of battery swaps
- system failures
- battery swaps
- any additional maintenance
- photographs

d. Standard Nominal Clearing Test Results

Figure 43 shows a photograph of the standard mission test layout. Five vials are arranged in a very specific order.

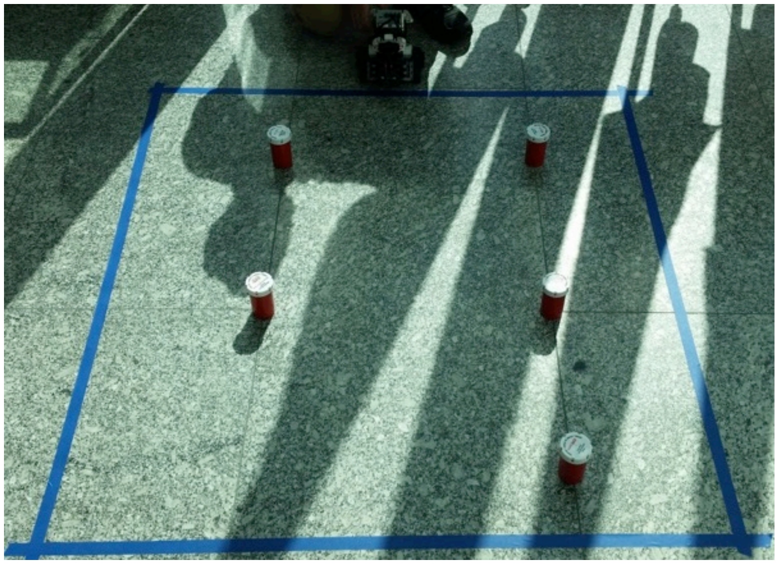

Figure 43. SNCT Layout Photograph

- TCV Standard Mission Results:

The TCV performed the standard mission five times. Each mission had a success rate of 100% with no vials missed or knocked over. No faults resulting in an essential function failure (EFF) or mission abort were experienced. That average time to retrieve a single vial was 29 seconds and the average time to complete the entire clearing mission was two minutes and 26 seconds. No battery changes were required during testing. No maintenance was required during testing. A learning curve was observed and the clearing times were slightly quicker after the first few runs.

The TCV did not have the capability to distinguish the vials during testing therefore no data recorded relating to identification of vials.

- ACV Standard Mission Results:

The ACV performed the standard mission five times. The average mission success rate was 96% with the ACV missing one vial. The ACV appeared to see the vial that was missed but did not properly line up with the vial causing it to miss. No vials were knocked over during testing. The vial that was missed was later retrieved meaning eventually the ACV retrieved all of the vials. Two faults resulting in an EFFs were experienced. The system required a restart to correct the fault.

The average time to retrieve a single vial was 49 seconds and the average time to complete the entire clearing mission was nine minutes. No battery changes were required during testing. No maintenance was required during testing.

The ACV did not have the capability to distinguish the vials during testing therefore no data recorded relating to identification of vials.

4. Non-Standard Clearing Test

a. Objective

- The objective the non-standard clearing test (NSCT) is to give a Non-Standard mission representative test to verify the SNCT did not provide any bias between the TECHMAN ACV and TCV.

b. Criteria and Data Analysis

- The results of the NSCT were used to determine the performance, reliability, and safety of the TECHMAN ACV and TCV and provide a comparison against the SNCT to ensure bias was not introduced. The NSCT provided input to evaluation of:
  - KSA 1–3
  - KSA 5
  - KSA 5
  - KSA 6–13
  - APA 3–5

c. Test Procedures and Data Required

Figure 44 shows the 16 square foot test area for the NSCT. The vials were placed in a random pattern. The TECHMAN ACV and TCV were run through the SNCT one time each. Each system started in the corral area then proceeded to find and retrieve the vials and return the vials to the corral area. Time to clear the area was recorded along

with the number of vials returned, number of battery swaps required, and any system failures or anomalies. The NSCT results were compared against the SNCT results.

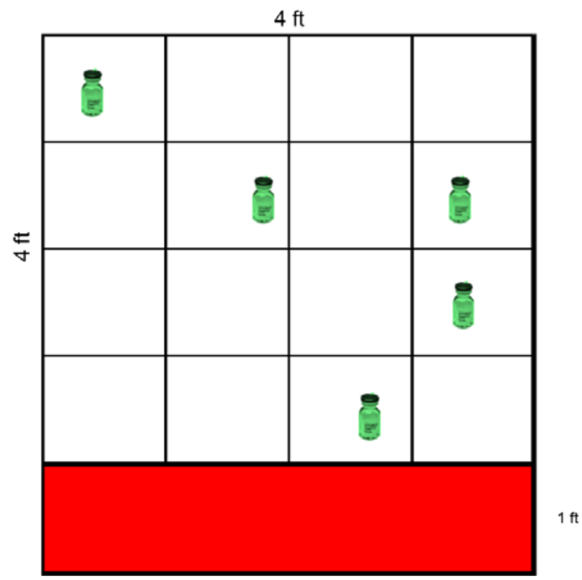

Figure 44. NSCT Vial Configuration

The following data were recorded:

- overall time to clear area
- time per vial
- average time per vial
- number of vials returned
- correct or incorrect identification of vials
- number of battery swaps
- system failures
- battery swaps
- any additional maintenance
- photographs

d. Non-Standard Clearing Test Results

Figure 45 is a photograph of the standard mission test layout. Five vials are arranged in a specific order.

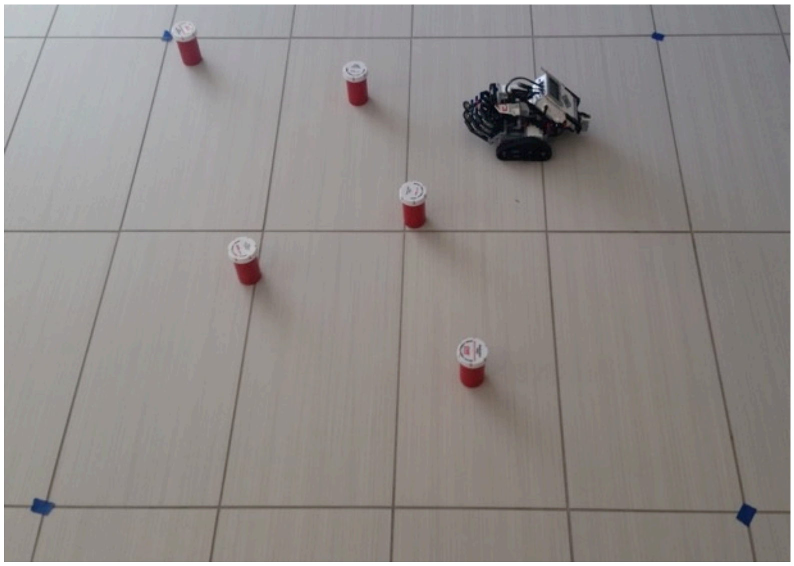

Figure 45. NSCT Layout Photograph

- TCV Non-Standard Mission Results:

The TCV performed the Non-Standard clearing test five times. Each mission had a success rate of 100% with no vials missed or knocked over. No faults resulting in an EFF or mission abort were experienced. That average time to retrieve a single vial was 31 seconds and the average time to complete the entire clearing mission was two minutes and 35 seconds. No battery changes were required during testing. No maintenance was required during testing.

The TCV did not have the capability to distinguish the vials during testing therefore no data recorded relating to identification of vials.

- ACV Non-Standard Clearing Test Mission Results:

The ACV performed the Non-Standard clearing test two times. The average mission success rate was 59%. When there were two vials that did not have much separation in the ACV's sightline, the ACV appeared to see them as one. The ACV would then proceed to the center of the two vials causing it to miss both vials. Because of this, the ACV required many runs to clear the entire test area. The operator had the ACV perform its search from different areas, which helped the problem but did not eliminate the issue entirely. Five faults resulting in an EFF were experienced. The system required a restart to correct the faults.

The average time to retrieve a single vial was 47 seconds and the average time to complete the entire clearing mission was 14 minutes 30 seconds. No battery changes were required during testing. No maintenance was required during testing.

The ACV did not have the capability to distinguish the vials during testing therefore no data recorded relating to identification of vials.

C. EVALUATION

1. Requirements And Mission Evaluation

The ACV and TCV were evaluated against system requirements and against the DRM. Table 19 is the rating criteria for meeting the requirements and effectiveness, suitability, and survivability (ESS). Table 20 is the rating criteria for operational impact against the DRM. The criteria described in the tables were used to assess the robots ability to meet the KPP and attributes.

Table 19. ESS Assessment Four-Color Rating Scheme and Definitions (after Department of the Army 2011)

Rating	Color	Symbol	Program Requirement Rating Definition
Met	Green	G	A green rating indicates that the system satisfied the threshold requirement as stated in the requirement document and/or applicable regulatory document with justified confidence according to the T&E strategy.
Partially Met	Yellow	Y	A yellow rating indicates that the system: • Satisfied part of the requirement. • Met the threshold requirement as stated in the requirement document and/or applicable regulatory document with low confidence according to the T&E strategy. May include recommendations for a path forward to address deficiencies to become operationally effective or sui . • Required a workaround in order to satisfy the requirement.
Not Met	Red	R	A red rating indicates that the system: • Did not meet the minimum threshold requirement as stated in the requirement document and/or applicable regulatory document. • May include recommendations for a path forward to address deficiencies to become operationally effective or suitable.
Unknown	Grey	U	A grey rating indicates that the system performance for the particular requirement is not known and cannot be determined from the information and data available.

Table 20. Operational Impact Rating and Color Scheme (after Department of the Army 2011)

Rating	Symbol	Operational Impact Rating Definition
Similar or Enhanced Capability	G	The system evaluation finding indicates that the operational capability is similar to current capabilities, provides an improved capability, or provides a new capability, relative to the requirement.
Reduced Capability	Y	The system evaluation finding indicates that the system may result in decreased mission capability, relative to the requirement.
Significantly Degraded Capability	R	The system evaluation finding indicates that the system may have significant, negative impact on mission capability, relative to the requirement.
Unknown	U	The system impact on mission operations is not known and cannot be determined from the information and data available.

a. ACV Evaluation

Table 21 covers the evaluation ratings of the ACV in comparison to the KPPs, KSAs, and Attributes along with the operational impact. The table also contains recommendations for the ACV. The overall evaluation of the ACV is the system effective in completing its mission. However, there are many limitations causing it to complete its mission in a degraded manner and requiring more operator input.

Table 21. ACV Assessment Requirements, Ratings, and Recommendations

Operational Task	**Requirement (source): description**	**Requirement Rating**	**Operational Impact**	**Recommendation and/or Materiel Release Condition**
Pass and receive mission information	KSA1: The robot shall notify the operator of system malfunctions	G	G	Have discriptor of the errors to help with problem dignosis
	KSA2: The robot shall store a mission log file for retrieval by the operator	R The robot did not store a mission log	Y Users would not be able to retrive mission data	Future updates of the robot shall keep a log file
	KSA3: When returning a vial to the corral, the robot shall play a distinct sound for a “hazardous vial” and a different sound for an inert vial	U The robot did not determine vial type or play sounds	Y Users would not know the vial type	Future updates of the robat should notify the operator of mission outcome
Operate in intended environment	KPP1: The robot shall run for 2 hours without swapping batteries	G	G	None
	KPP2: The system shall be transportable in Two containers, with the weight of each container not to exceed 35 lbs	G	Y System is easily damaged during transport and parts can be lost	Extra caution should be used during transport
	KSA4: The robot shall be powered by 6 AA batteries or rechargeable equivalent	G	G	None

Operational Task	Requirement (source): description	Requirement Rating	Operational Impact	Recommendation and/or Materiel Release Condition
	KSA5: The system shall operate in a manner safe to its operators	G	G	None
	APA 1: Batteries shall be replaceable within two minutes	G	Y Changing batteries requires some disassembly of the robot	User should use caution to ensure parts are not lost or damaged during battery changes
	APA 2: The system shall comply with the FCC's requirements for a Class D device	G	G	None
	APA 3: The system shall be operated by not more than one servicemember	G	G	None
Propel itself under its own power, including while carrying vials	KSA6: The robot shall traverse terrain of smooth concrete or blacktop surfaces	G	G	None
	KSA7: The robot shall be able to change its heading to any 360 degree orientation	G	Y Improper triming causes the robot to be out of position	Allow for robot to automatically "trim" to account for the different type of surfaces encountered
Clear a given area of radiological threats	KPP3: The robot shall clear a rectangular area (the "target area") of a defined size	G	G	None
	KPP4: The robot shall secure all vials and return them to the corral for disposal by trained personnel and a separate system with a 0.9 probability	R The system had an 0.59 probability of securing vials	Y Significat mission delays will occur with possible missed vials.	Future updates of the robot should increase probability of retrieving a vial.
	KSA8: The robot shall distinguish a "hazardous" colored vial from vials of other colors with a 90% probability of distinction	R The robot did not determine vial type	Y Users would not know the vial type	Future updates of the robat should obtain this capability

Operational Task	Requirement (source): description	Requirement Rating	Operational Impact	Recommendation and/or Materiel Release Condition
	KSA9: The system shall detect vials under fluorescent lighting conditions	G	G	None
	KSA12: The system shall have the 0.75 probability of completing a 2 mission hours without an essential function failure.	Y Several EFFs were experienced which required a system restart to correct	Y EFFs would cause mission delays and possibily place servicemembers in danger	Increase reliability
	KSA13: The system shall have a 0.95 probability of completing 2 mission hours without a system abort	G	G	None
	APA4: The system shall not exceed 0.04 MMH/OH ratio	R Unscheduled maintenance time was high due to the number to EFFs	Y EFFs would cause mission delays and possibily place servicemembers in danger	EFFs need to be reduced to improve the amount of unscheduled maintenance.
	APA5: The system shall pass the Standard Mission and Non-Standard Clearing Test Pattern in 15 minutes	Y Average mission time met the req but some missions required more time	Y Mission delays could be experienced	Improving detecting and retrieving capability will improve the mission time

As can be seen in the evaluation table, the ACV did not meet some requirements set forth in the CDD. The robot did not store a log file and did not distinguish vials. Because it did not distinguish vials it also did not notify the operator of the type of vial found. While this did not have a large effect on mission completion, it does require more work by the cleanup team and could possibly place them in a dangerous situation. Design improvements should be made to satisfy this capability if the program continues past MS B.

The next issue found during testing which would have a large operational impact is the low probability of detecting vials, especially vials that are close together. The robot eventually was able to clear all the vials but mission time significantly increased due to the extra time taken to travel out and scan again for vials. If the system is operating in an area without line of sight, the operator may not have much confidence that the system has collected all the vials. This could expose users to hazards in an area they thought was clear. Later updates of the robot may increase search accuracy by better sensors or different search patterns.

The ACV experienced a number of EFFs during testing. All of the EFF were experienced while starting the system and were corrected by a full system restart. However, the EFFs caused delays leading to longer mission time and more operator interaction.

b. TCV Evaluation

Table 22 covers the evaluation ratings of the TCV in comparison to the KPPs, KSAs, and Attributes along with the operational impact. The table also contains recommendations for the TCV. The overall evaluation of the TCV is the system effective in completing its mission. However, there are some limitations causing it to complete its mission in a degraded manner and requiring more input from the operator. The limitations are the same as the ACV with regards to keeping a log file and distinguishing vials.

Table 22. TCV Assessment Requirements, Ratings, and Recommendations

Operational Task	**Requirement (source): description**	**Requirement Rating**	**Operational Impact**	**Recommendation and/or Materiel Release Condition**
Pass and receive mission information	KSA1: The robot shall notify the operator of system malfunctions	G	G	Have descriptor of the errors to help with problem dignosis
	KSA2: The robot shall store a mission log file for retrieval by the operator	R The robot did not store a mission log	Y Users would not be able to retrive mission data	Future updates of the robot shall keep a log file
	KSA3: When returning a vial to the corral, the robot shall play a distinct sound for a “hazardous vial” and a different sound for an inert vial	U The robot did not determine vial type or play sounds	Y Users would not know the vial type	Future updates of the robat should notify the operator of mission outcome
Operate in intended environment	KPP1: The robot shall run for 2 hours without swapping batteries	G	G	None
	KPP2: The system shall be transportable in Two containers, with the weight of each container not to exceed 35 lbs	G	Y System is easily damaged during transport and parts can be lost	Extra caution should be used during transport
	KSA4: The robot shall be powered by 6 AA batteries or rechargeable equivalent	G	G	None
	KSA5: The system shall operate in a manner safe to its operators	G	G	None
	APA 1: Batteries shall be replaceable within two minutes	G	Y Changing batteries requires some disassembly of the robot	User should use caution to ensure parts are not lost or damaged during battery changes
	APA 2: The system shall comply with the FCC’s requirements for a Class D device	G	G	None

Operational Task	Requirement (source): description	Requirement Rating	Operational Impact	Recommendation and/or Materiel Release Condition
	APA 3: The system shall be operated by not more than one servicemember	G	G	None
Propel itself under its own power, including while carrying vials	KSA6: The robot shall traverse terrain of smooth concrete or blacktop surfaces	G	G	None
	KSA7: The robot shall be able to change its heading to any 360 degree orientation	G	G	None
Clear a given area of radiological threats	KPP3: The robot shall clear a rectangular area (the “target area”) of a defined size	G	G	None
	KPP4: The robot shall secure all vials and return them to the corral for disposal by trained personnel and a separate system with a 0.9 probability	G	G	None
	KSA8: The robot shall distinguish a “hazardous” colored vial from vials of other colors with a 90% probability of distinction	R The robot did not determine vial type	Y Users would not know the vial type	Future updates of the robat should obtain this capability
	KSA12: The system shall have the 0.75 probability of completing a 2 mission hours without an essential function failure.	G	G	None
	KSA13: The system shall have a 0.95 probability of completing 2 mission hours without a system abort	G	G	None
	APA4: The system shall not exceed 0.04 MMH/OH ratio	G	G	None

Operational Task	Requirement (source): description	Requirement Rating	Operational Impact	Recommendation and/or Materiel Release Condition
	APA5: The system shall pass the Standard Mission and Non-Standard Clearing Test Pattern in 15 minutes	G	G	None

2. ACV And TCV Comparison

One of the research questions involved comparing impacts to the mission for the ACV and TCV. The ACV and TCV perform the same mission; however, the service members use the systems in a different manner. As covered earlier in the report, the operator controls the TCV where the ACV clears the area on its own.

Table 23 shows the success rate, average time to clear an individual vial, and the overall average mission time. The result shows that the TCV is more accurate at clearing the vials and was able to complete the mission in significantly less time. This is the main advantage of the TCV. If one operator is able to focus her time entirely on one mission area, then the TCV should be used.

Table 23. Clearing Test Results

Parameter	ACV (Standard)	ACV (Non-Standard)	TCV (Standard)	TCV (Non-Standard)
Success Rate Standard %	96	59	100	100
Ave Time Per Vial (seconds)	49	47	29	31
Ave Mission Time (seconds)	540	870	146	155

There are some disadvantages to using the TCV for the clearing mission however. The first and main disadvantage is it requires the operator's full attention throughout the clearing mission. This means that one operator can only operate one TCV at time. A second disadvantage of this system is it requires the operator to have a line of sight of the clearing area.

The main advantage of the ACV on the other hand is the operator can start the system on the clearing mission and then move his attention to other tasks. The operator also does not need line of sight of the clearing area. This allows one operator the ability to run multiple ACV systems at a time which affords him the ability to clear more area in less overall mission time.

The current ACV has some disadvantages due to its low probability of detection and must be restarted after each clearing run requiring more operator time and input. Another disadvantage of the ACV is more training is required for setting the system up for the clearing mission. Operators must input the clearing parameters of the clearing area before the mission is started.

Following the JCIDS/DAS process, if the program proceeded beyond MS B the systems would continue to be refined and some of the disadvantages could be corrected making the ACV more effective and requiring less operator input.

In the current state of the TECHMAN systems the TCV is likely the better option for completing the mission. However, if improvements were made to address accuracy and reduce mission time, the ACV it would become the better option.

VII. SYSTEM SUPPORTABILITY

A. LIFE-CYCLE COST

Life-cycle cost estimations are based on the notional life-cycle cost estimates shown in Figure 46. The percentages are approximations and provide a basis for estimation of the cost over each life-cycle.

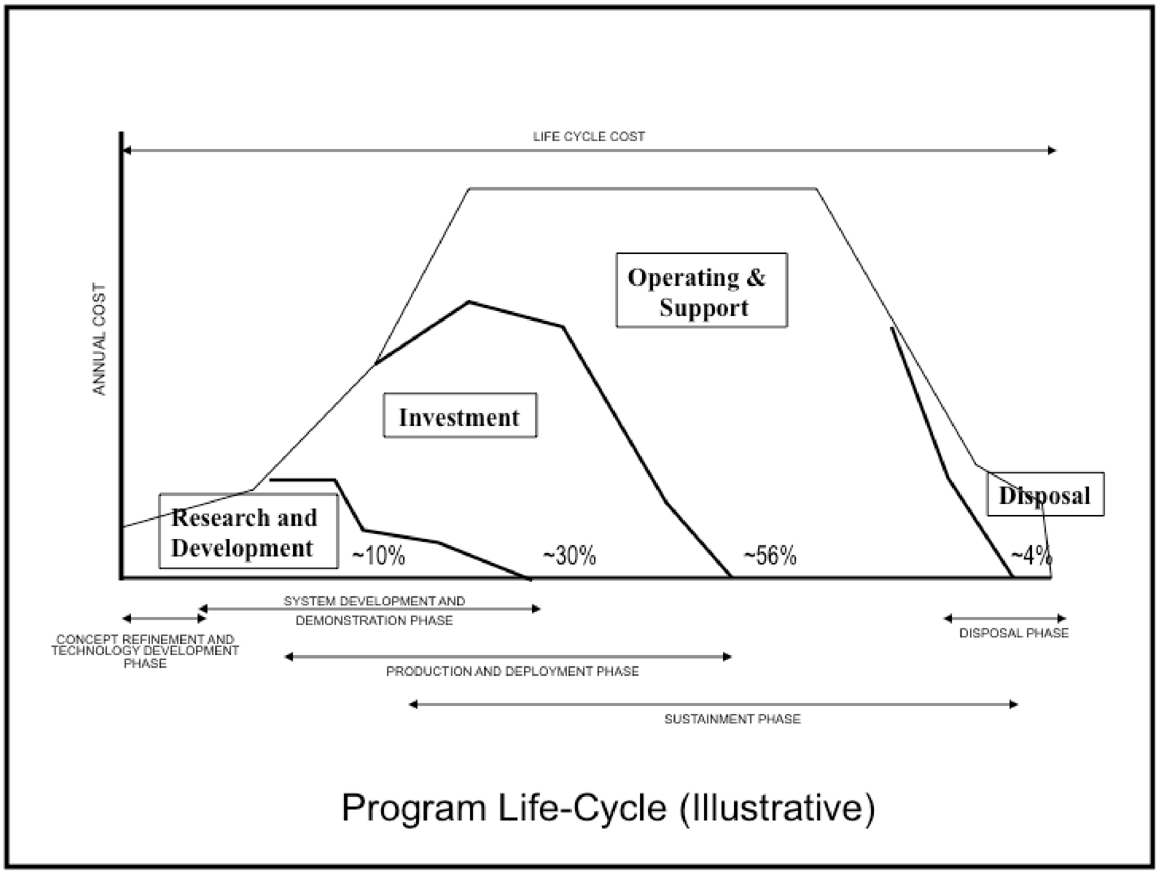

Figure 46. Notional Profile of Annual Program Expenditures (after *Defense Acquisition Guidebook*, Section 3.1.2)

1. Research And Development Cost

The leJOS programming environment is free to use; however, there was some time involved in our team members becoming familiar with the Java language, and the leJOS-specific libraries and tools. Software development costs include these hours spent learning the tools and the hours spent writing the code. The ACV software package took four times the amount of time in preparing and setting up the leJOS environment than the TCV software package. In time spent writing the code the ACV software package required three times the amount of time than the TCV software package. Table 24 summarizes the hours spent in learning leJOS, setting up the environment, and writing the code for both vehicles.

Table 24. Software Development Labor Hours

Platform	Hrs. learning leJOS/setting up environment	Hrs. Writing Code	Total Hrs.
ACV	20	60	80
TCV	5	20	25

The hours spent in designing the robot are included in the Mechanical Engineering hours. The two designs use the same hardware configuration and the hardware design costs are shared between the two vehicles. The final design is documented with a parts list, model and assembly instructions using the LEGO Digital Designer (LDD).

The system cost includes the cost of piece parts, assembly, training, operators, and support equipment. Piece parts and assembly costs are the same for both the TCV and ACV. Figure 47 lists the itemized cost of the piece parts. The parts list in Figure 47 was exported from the LDD model while the prices of the parts was obtained from LEGO.com or equivalent vendor sites online. The bill of materials (BOM) to reproduce an ACV or TCV unit is $376.66. The TCV requires a laptop to run which is an additional hardware cost of approximately $400.

Brick	Name	Picture	Part	Color code	Qty.	Unit Price	Total Cost
4246901	TYRE LOW NARROW Ø14.58 X 6.24		50951	26 - Black	2	$ 0.20	$ 0.40
4494222	WEDGE-BELT WHEEL Ø24		4185	194 - Medium Stone Grey	2	$ 0.10	$ 0.20
6028041	TYRE FOR WEDGE-BELT WHEEL		2815	26 - Black	2	$ 0.15	$ 0.30
4299389	RIM WIDE W.CROSS 30x20		56145	26 - Black	4	$ 0.55	$ 2.20
4502834	CATERPILLAR TRACK		53992	26 - Black	2	$ 0.50	$ 1.00
6024581	CABLE 250 MM		11145	40 - Transparent, 26 - Black	6	$ 6.54	$ 39.24
4297187	Cable 208mm		55804	40 - Transparent, 26 - Black	1	$ 2.34	$ 2.34
6008919	MS, EV3, SENSOR, COLOUR		95650	194 - Medium Stone Grey, 1 - White, 26 - Black, 102 -	2	$ 25.83	$ 51.66
6008472	MS, EV3, TOUCH SENSOR		95648	194 - Medium Stone Grey, 1 - White, 315 - Silver	1	$ 14.50	$ 14.50
6008577	SMALL MOTOR		99455	21 - Bright Red, 194 - Medium Stone Grey, 1 -	1	$ 24.29	$ 24.29
6063629	MS-EV3, ULTRASONIC SENSOR		95652	194 - Medium Stone Grey, 1 - White, 26 - Black, 41 - Tr.	1	$ 28.92	$ 28.92
6057952	MS 2013 ENGINE		95658	21 - Bright Red, 194 - Medium Stone Grey, 1 -	2	$ 24.29	$ 48.58
6009996	MS-EV3, P-BRICK		95646	1 - White, 194 - Medium Stone Grey, 40 -	1	$ 115.50	$ 115.50
4142822	TECHNIC 3M BEAM		32523	26 - Black	8	$ 0.15	$ 1.20
4142135	TECHNIC 5M BEAM		32316	26 - Black	9	$ 0.20	$ 1.80
4495935	TECHNIC 7M BEAM		32524	26 - Black	4	$ 0.30	$ 1.20
4120017	TECHNIC ANG. BEAM 4X2 90 DEG		32140	26 - Black	2	$ 0.30	$ 0.60
4645732	TECHNIC 9M BEAM		40490	26 - Black	2	$ 0.10	$ 0.20
4552347	T-BEAM 3X3 W/HOLE Ø4.8		60484	26 - Black	1	$ 0.30	$ 0.30
4522933	TECHNIC 13M BEAM		41239	26 - Black	4	$ 0.40	$ 1.60
4542573	TECHNIC 15M BEAM		32278	26 - Black	3	$ 0.10	$ 0.30
4142823	TECHNIC ANG. BEAM 3X5 90 DEG.		32526	26 - Black	6	$ 0.30	$ 1.80
4140327	TECHNIC ANGULAR BEAM 3X7		32271	26 - Black	2	$ 0.30	$ 0.60
4111998	DOUBLE ANGULAR BEAM 3X7 45°		32009	26 - Black	10	$ 0.50	$ 5.00
4239601	1/2 BUSH		32123	24 - Bright Yellow	11	$ 0.10	$ 1.10
4142865	2M CROSS AXLE W. GROOVE		32062	21 - Bright Red	6	$ 0.10	$ 0.60
4121715	CONNECTOR PEG W. FRICTION		2780	26 - Black	59	$ 0.10	$ 5.90
4211815	CROSS AXLE 3M		4519	194 - Medium Stone Grey	6	$ 0.10	$ 0.60
4227155	BUSH FOR CROSS AXLE		6590	21 - Bright Red	8	$ 0.15	$ 1.20
4184169	BALL WITH FRICTION SNAP		6628	26 - Black	4	$ 0.10	$ 0.40
4206482	CONN.BUSH W.FRIC./CROSSALE		43093	23 - Bright Blue	19	$ 0.10	$ 1.90
4514553	CONNECTOR PEG W. FRICTION 3M		6558	23 - Bright Blue	21	$ 0.25	$ 5.25
6031821	CROSSAXLE 3M WITH KNOB		6587	138 - Sand Yellow	4	$ 0.10	$ 0.40
4254606	ANGLE ELEMENT, 0 DEGREES [1]		32013	21 - Bright Red	2	$ 0.20	$ 0.40
4211553	CATCH W. CROSS HOLE		32039	194 - Medium Stone Grey	2	$ 0.20	$ 0.40
4211639	CROSS AXLE 5M		32073	194 - Medium Stone Grey	8	$ 0.20	$ 1.60
4188298	CROSS BLOCK 90°		6536	21 - Bright Red	4	$ 0.15	$ 0.60
4211758	HUB Ø11,2 X 7,84		42610	194 - Medium Stone Grey	2	$ 0.15	$ 0.30
6006140	BEAM 1X2 W/CROSS AND HOLE		60483	26 - Black	4	$ 0.10	$ 0.40
6083620	CROSS AXLE 4M WITH END STOP		87083	199 - Dark Stone Grey	2	$ 0.10	$ 0.20
4140806	2M FRIC. SNAP W/CROSS HOLE		32054	21 - Bright Red	4	$ 0.25	$ 1.00
4128598	DOUBLE CROSS BLOCK		32184	21 - Bright Red	4	$ 0.30	$ 1.20
4234429	ANGLE ELEMENT, 180 DEGREES		32034	21 - Bright Red	1	$ 0.20	$ 0.20
4175442	CROSS BLOCK 3M		42003	21 - Bright Red	2	$ 0.10	$ 0.20
4535768	CROSS AXLE 9M		60485	194 - Medium Stone Grey	1	$ 0.10	$ 0.10
4499858	CROSS AXLE 8M WITH END STOP		55013	199 - Dark Stone Grey	6	$ 0.10	$ 0.60
4189936	ANGLE ELEMENT 135 DEG. [4]		32192	21 - Bright Red	2	$ 0.30	$ 0.60
4211888	MODULE BUSH		32138	194 - Medium Stone Grey	2	$ 0.10	$ 0.20
4141300	LT STEERING GEAR		32293	26 - Black	2	$ 0.10	$ 0.20
4630114	CROSS BLOCK/FORM 2X2X2		92907	194 - Medium Stone Grey	2	$ 0.11	$ 0.22
4225033	BEAM 3 M. W/4 SNAPS		48989	194 - Medium Stone Grey	8	$ 0.10	$ 0.80
4539880	BEAM FRAME 5X7 Ø 4.85		64179	194 - Medium Stone Grey	2	$ 0.73	$ 1.46
4540797	BEAM H. FRAME 5X11 Ø4.85		64178	194 - Medium Stone Grey	2	$ 0.57	$ 1.14
4565452	CONICAL WHEEL Z12		6589	5 - Brick Yellow	1	$ 0.30	$ 0.30
4177431	DOUBLE CONICAL WHEEL Z12 1M		32270	26 - Black	2	$ 0.30	$ 0.60
4177430	DOUBLE CONICAL WHEEL Z20 1M		32269	26 - Black	3	$ 0.10	$ 0.30
4248204	TECHNIC ANGULAR WHEEL		32072	26 - Black	4	$ 0.10	$ 0.40
4255563	DOUBLE CONICAL WHEEL Z36		32498	26 - Black	4	$ 0.54	$ 2.16
			Hardware Count:				**292**
			Hardware Cost:			**$**	**376.66**

Figure 47. Piece Part Costs

Hourly rates obtained from the Bureau of Labor Statistics National Occupational Employment Statistics are used in estimating the design and development costs. During the project the team members performed functions similar to a PM, systems engineer (SE), mechanical engineer (ME), software developer (SD), and a technical writer (TW). Overhead costs are factored in at a conservative 30% of the labor costs. Table 25 and Table 26 summarize the estimated labor costs for the TCV and ACV, respectively.

Table 25. Current TCV Wages and Overhead Costs

Labor Act	Hourly Rate	Total Hours	Wages	Overhead
PM/SE	$55.81	135	$7,534.35	$2,260.31
ME	$41.31	270	$11,153.70	$3,346.11
SD	$46.28	25	$1,157.00	$347.10
TW	$33.80	190	$6,422.00	$1,926.60
Total			**$26,267.05**	**$7,880.12**

Table 26. Current ACV Wages and Overhead Costs

Labor Act	Hourly Rate	Total Hours	Wages	Overhead
PM/SE	$55.81	135	$7,534.35	$2,260.31
ME	$41.31	270	$11,153.70	$3,346.11
SD	$46.28	80	$3,702.40	$1,110.72
TW	$33.80	190	$6,422.00	$1,926.60
Total			**$28,812.45**	**$8,643.74**

The project is approximately 50% of the way through the research and development (R&D). The projected total for completion of the R&D life-cycle is summarized in Table 27.

Table 27. R&D Life-Cycle Phase Estimated Cost

Vehicle	Wages	Overhead	Hardware	Current Total	Projected Total
TCV	$26,267.05	$7,880.12	$768.66	$34,914.83	**$69.829.65**
ACV	$28,812.45	$8,643.74	$367.66	$37,823.85	**$75,647.69**

2. Investment Cost

Investment cost is estimated to be 30% of the life-cycle cost. Projections from the R&D estimate provide a basis for the estimation of the investment life-cycle cost. Table 28 summarizes the estimate for the life-cycle cost.

3. Operating and Support Cost

Operating and Support (O&S) cost is estimated to be 56% of the life-cycle cost. Projections from the R&D estimate provide a basis for the estimation of the O&S life-cycle cost. Table 28 summarizes the estimate for the life-cycle cost.

4. Disposal Cost

Disposal cost is estimated to be 4% of the life-cycle cost. Projections from the R&D estimate provide a basis for the estimation of the disposal life-cycle cost. Table 28 summarizes the estimate for the life-cycle cost.

5. Total Life-Cycle Cost

The life-cycle cost includes the costs over each of the life-cycle phases. Table 28 summarizes these costs of each phase and the life-cycle cost for each vehicle. From the extrapolations based on current cost accruals the ACV's life-cycle cost is estimated to be 8.3% greater than the life-cycle cost of the TCV.

Table 28. Summary of Life-cycle Costs for TCV and ACV

Life-cycle Phase	TCV	ACV
R&D	$69,829.65	$75,647.69
Investment	$209,488.95	$226,943.07
O&S	$391,046.04	$423,627.06
Disposal	$27,931.86	$30,259.08
LCC	**$698,296.50**	**$756,476.90**

B. TRAINING

1. Common Training

Most of the common training would not change between the ACV and TCV, simply because of the device's mission. The clearance vehicle only brings hazardous vials from a dangerous location to a less dangerous location, where the operator must dispose them. We expect most of the operator training will consist of how to properly dispose of a hazardous vial and a substantially smaller amount of the training will consist of training on the clearance vehicle.

For the portion of the operator training focused on clearance vehicles, the largest portion would probably cover the operator level maintenance tasks covered in the operator's manual portion of the Technical Manual. Due to the common system design for the Clearance Vehicles, the operator's maintenance of the CVs themselves will likely be the same. Tasks include replacing the batteries, replacing the treads, and loading software updates onto the system.

2. TCV Training

The TCV's training is straight forward as the system is fairly simple. The operators will need to know how to turn on the field laptop, turn on the robot, and connect the two. Once connected the operator interface is straightforward. The OCU has buttons for forward, reverse, steer left, steer right, speed control, lift arm up, and lift arm down.

The TCV does have a learning curve for the operator that should be taken into consideration. It will take a new operator some time to learn the controls and how the robot responds to input. Also, depending on the experience the operator has operating teleoperated system additional time may be need to learn to drive the system.

3. ACV Training

The ACV specific tasks that operators need to be trained on are largely diagnostics, which are useful for the level maintainers. Operators will need to know how to properly conduct and record the results of the four calibration missions so they can have their system recalibrated. Recalibrating the system is not an operator level task.

The operation of the system is fairly straightforward. The ACV requires the operator to cordon off the area and then press a single button. Because the ACV is autonomous, no further operator intervention is necessary until the ACV returns. The actual operation of the ACV is a small part of the operator's overall job, and the ACV Operator's training should reflect that.

C. MAINTENANCE

1. Evaluation of Maintainability

No reliability or maintainability requirements were tested during the test and evaluation portion of the project. The TECHMAN systems were not utilized enough to require maintenance tasks. However, the test team gained some insights during system development and testing of the systems.

Testing found that the ACV can take around 10 minutes longer per mission than the TCV. Over the lifetime of the system, this would lead to more battery swaps and more wear on the batteries, tracks, and drive motors. If the program were to continue post MS B, then the lifespan of the tracks, motors, and other parts would be determined. Knowing this lifespan along with system reliability would allow for a proper maintainability assessment.

Both the ACV and TCV were tested with an OCU, which is operated on a standard issue laptop. However, the TCV requires constant use of the laptop to control the system, which means the laptop, will have more use during mission. This will lead to more batteries needed to support the mission and lead to a shorter life span for the laptop.

Again, if the program proceeded post MS B, then the laptop maintenance needs would be found and a determination would be made on the maintenance needs for a mission.

2. Scheduled Maintenance

No special tools are required to perform any maintenance tasks for the TECHMAN systems. At this time, there are no documented scheduled maintenance tasks. Likely scheduled maintenance at defined intervals would include:

- check the tracks for wear
- check the drives wheels and road wheels for wear and proper lubrication
- check the drive motors for wear and proper lubrication
- check the claw motor for wear and proper lubrication
- check the claw pivot points for wear and proper lubrication
- check the battery compartment for corrosion and proper fit of batteries
- clean sensors
- software health check

D. TRANSPORTABILITY

No transportability testing was complete due to being early in the JCIDS process and limitations of the project. However, some observations were made and a quick analysis was completed.

Figure 48 is a transport case that would meet the requirements to transport a single TECHMAN System. The case is built military specifications and cost around $220. Custom foam padding would need to be made to fit the TECHMAN robot and accessories would cost an additional $100 per case bringing the total cost of the transport cases to $320.

Figure 48. Pelican Transport Case

Transporting the system with this case will meet the transportability requirement as written in the CDD.

When transporting the TECHMAN systems to the T&E site, the team discovered the systems are likely to fall apart during transport. While using a custom fit case will help with that issue, it will not eliminate it. The systems should be treated as fragile cargo during transport, and someone at the mission site time should be dedicated to ensuring the system remained intact or reassembling any pieces that detached from the system.

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VIII. RECOMMENDATIONS AND CONCLUSIONS

A. TECHNICAL OUTCOMES

Within the team's constraints, the TECHMAN Team designed, built, and programmed two UGVs: an Autonomous Clearance Vehicle and a Teleoperated Clearance Vehicle. Additionally, the team performed an abbreviated systems engineering process in order to ensure the TECHMAN systems were built within standards (both technical and schedule) and with quality and life-cycle concerns in mind. Within the limits of the model, the process was a success. The team successfully delivered two well-engineered prototypes that could fulfill the needed capabilities and met most of the requirements.

Objectives that were not achieved were outside the scope of the model process. For example, the team had to scale down the planned search area from 20 ft^2 to 4 ft^2 due to the limitations of the sensors. On a real-world project, the team would have had the opportunity to substitute different sensors to achieve a greater scanning radius, but due to the limits of the provided kit, the team could not use a different model of sensor than planned. Lack of sensor range also prevented the devices from being able to detect the vials' color.

A unique problem faced by the ACV was location finding. Due to the extremely limited capability of the tachometers in the provided motors they could not be used for dead reckoning. Additionally, lack of capability of the color sensor prevented the robot from using the blue tape perimeter as a landmark while navigating. Use of better tachometers or an absolute positioning solution (such as GPS) would have been options on a real system, but were not available to the TECHMAN team due to the limitations of the provided kit.

B. SUMMARY OF RESEARCH QUESTIONS

1. How well does the JCIDS/DAS process support the acquisition and development of UGVs?

As discussed in the first chapter of this report, the majority of UGVs used by the DOD are acquired using the rapid-fielding process, which does not follow a structured process such as JCIDS/DAS. The JCIDS/DAS process provides structure to ensure programs cover all the needed life-cycle items and follow smart SE. To see if following JCIDS/DAS was actually helpful, this project used the essence of JCIDS/DAS to MS B. This included developing requirements from a user need, requirement analysis, AOA, using SE for system Design, T&E, and LCC.

After completing this limited scope, the TECHMAN team determined that using the JCIDS/DAS process does a very good job of supporting the acquisition and development of UGVs. As found during the initial research, many of the current UGVs are difficult to support and do not meet performance needs. The JCIDS/DAS process would reduce the number of programs with problems like that be fielded. To pass Milestones, programs must meet ESS requirements and stay within a budget.

Another discovery was that rapid-fielded programs have a one step process in which the system is designed, built, and fielded. If the TECHMAN systems were developed as a rapid-fielded program they, the robots would be fielded "as is." Thus, as shown in this team's evaluation, the systems would not meet the user needs. However, the project was in the technology and development phase of JCIDS/DAS and had just reached MS B. The team proved that the requirements were realistic and the technology was available to meet them, which was one of the main goals of a pre MS B program. The program would continue on within the JCIDS/DAS process in the engineering and manufacturing phase to MS C and after that the production and deployment phase. During the phases following MS B, improvements to the TECHMAN systems would be made to ensure the systems meet the user need before being fielded.

The downside to using the JCIDS/DAS process was that it takes much longer than using the rapid-fielding process. As stated before, if the TECHMAN systems were being

completed as a rapid they would be fielded now. Whereas with the JCIDS/DAS process, the TECHMAN systems would have more work that must be done before fielding. The tradeoff of the extra time was a more effective, suitable, and supportable system.

2. What systems engineering approaches, tools, and techniques are critical to successful UGV projects?

Section H in the first chapter, along with the other chapters of the report, covers the SE methods used to develop the TECHMAN systems. Most, if not all, of the SE tools used to support the TECHMAN systems could be used on other UGVs within DOD. The SE tools and JCIDS/DAS process are very complementary to each other, which allowed for a successful project. If the project continued on the SE tools and JCIDS/DAS process would ensure the system would meet the user need from performance to supportability.

3. Given a set of performance and suitability requirements, how easily is it to accurately estimate cost and schedule for UGV projects within the JCIDS/DAS process?

Chapter VII covers the LCC for the TECHMAN system. Performance and suitability requirements drove the hardware and software design and the material needs of the system. The cost was directly related to the design time and material needs. The schedule has more flexibility and is tracked using EVM and project management.

If the performance and suitability requirements are clear and well understood by the project time then estimating cost and schedule is much easier. The TECHMAN systems requirements were well understood by the developers. Also, only minor changes were made to the requirements during the project, which did not have any cost or schedule impacts.

If the requirements were vague or made drastic changes during the project, then the cost and schedule estimates initially made would likely become wrong. Changes can cause an increase in cost and lengthen the schedule.

4. How much difference is there in the effort involved with developing teleoperated systems and the effort involved with developing autonomous systems?

Chapter V that discusses the design and Chapter VII that covers the LCC contain the details of the difference in effort involved with developing a teleoperated or autonomous system. To sum up the findings the autonomous system required more effort. The base platform of the TECHMAN systems was the same so development time was equal. However, software development required and additional 55 hours that resulted in an additional estimated cost of $2,545.2 in labor (9.7%).

In relation to UGVs within the DOD, autonomous systems will require additional effort then what was seen with the TECHMAN systems. The host platform would likely not be the same as a teleoperated one and would have more sensors and other subsystems to assist in the autonomous ability. Another aspect that could greatly increase effort with autonomous systems is ensuring the system is safe to the people around it. The TECHMAN ACV did not have much of a threat even if the system malfunctioned but large autonomous systems, especially ones with weapons, must operate in a manner that will not put people around the system in danger.

5. What are the tradeoffs in sensors and computation for autonomous and teleoperated UGVs?

As covered in the answer for the previous question, the ACV has greater computational needs to retain the autonomous ability. Additional code was written requiring more man-hours to develop. The tradeoff for this is having a system that does not need continuous attention of the operator.

As noted in chapter V the ACV and TCV used essentially the same host system. This means both systems had all of the sensor subsystems attached. This meant no tradeoffs were realized with the TECHMAN project. However, the TCV would not need the color sensors or ultrasonic sensor unless the user determined it was still useful for the operator. If the sensor were removed in later updates of the system, then less complexity, less power consumption, and reduced weight would be on the TCV making it cheaper and easier to maintain.

6. What are the impacts both with acquisition and mission completion when comparing autonomous and teleoperated UGVs?

Chapter VII that covers the LCC contains the time and cost difference between ACV and TCV systems as related to acquisition. Question 4 stated the autonomous system required an additional 55 hours and cost and 9.7% more. As far as the JCIDS/DAS process is concerned the TECHMAN systems did not find any differences or impacts other than the additional time required to develop the systems. All of the same SE processes and JCIDS/DAS items were required for both types of systems.

Chapter VI has the evaluation of the ACV and TCV systems, which covers the impacts to mission completion. The main take away is it would depend on the mission as to which is better. If the mission was covered exactly as written in the DRM then the TCV or teleoperated system would be better as it is faster and more accurate. However, if line of sight is not available, multiple areas need cleared, or operators are not able to give their undivided attention to the system, then the ACV is the better choice.

7. How much of a difference does the choice of a software engineering approaches make?

Chapter IV that has the AOA and chapter V that covers software design contains the details of the software engineering. This question is difficult to answer as only one software approach was used and only speculation can be given of the others. The main takeaway is developer familiarly made the largest impact. Using approaches and tools the developers were familiar with cut down on learning time and allowed the developers to better explain the software design to the other members of the team.

C. RECOMMENDATIONS FOR UGVS WITHIN JCIDS/DAS

Part of the project team's goal was to make recommendations for the JCIDS/DAS process or UGVs with in the DOD. The initial background research pointed to the issue with UGVs was that they used rapid fielding processes instead of the JCIDS/DAS. After performing this project and going through the simulated JCIDS/DAS process, the team determined that the JCIDS/DAS process is ideal for developing not only a system but

also necessary infrastructure to support that system. The process would take longer than going the rapid route due to extra requirements and more design iterations. However, going through these extra steps would ensure the system being fielded would meet the user's need.

The team did not develop any recommendations for the JCIDS/DAS process itself. The team's recommendation was that more programs should go through the process. Even though there may be a desire to cut corners and field a system faster and cheaper, it only hurts the DOD in the long run. The various components of JCIDS/DAS do add value to the overall program.

In regards to recommendations to UGVs, the project team gained some interesting insight. As covered in the report the team developed the user need from an actual ICD. However, using the Lego Mindstorms kits required the user needs and requirements to be fulfilled in a manner limited to the available technology. While developing the requirements, many discussions took place on how several of the requirements could actually be modified, giving the TECHMAN system a chance to meet the requirements. The insight gained is there is a balancing act with requirements and capabilities. Requirements may need to be iterated such that technology available or nearly available can meet them while also meeting the needs of the user and pushing the performance envelope.

Other insights are more obvious ones and were encountered as problems during the project. One of those is that requirements need to be clear and easy to understand. Knowing this trait, even while developing requirements, the team still had misunderstandings when developing the robots later in the project. Another insight is that requirements should be changed as little as possible, especially after the systems have been developed. Changing the requirements late in the program can increase cost and schedule. However, not changing requirements means the original requirements must be well written and cover all the user's needs and not be beyond available technology. The TECHMAN requirements needed minor changes after the initial prototype systems were constructed. The change was made because to the technology of the simulated systems

could not meet the tougher requirement. After the requirement was changed the autonomous system's software had to be updated to account for the new requirements. This added time, and if this were a real project, it would have added cost to the project. If the original requirements were written according to the capabilities of the existing technology then this problem would not have been encountered.

D. SUMMARY

Project TECHMAN used the JCIDS/DAS process to develop a teleoperated and an autonomous UGV system with the capability to clear an area of small containers. The system was developed through the Material Solution Analysis Phase to MS B. The team used SE tools to: define a mission, develop a user need, develop requirements, develop the system architecture, design and build an actual system, test the system, evaluate the test results, and perform a LCC analysis. The TECHMAN system was successful and able to complete the clearance mission. Through research and practical application found during the development of TECHMAN, the team learned that rigorous JCIDS/DAS process is ideal at ensuring the developed system will fulfill the user's need and be maintainable throughout the systems life-cycle. The team also discovered that maximizing the clarity of requirements initially while minimizing any changes to those requirements later increases the chances of a successful project.

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APPENDIX A: TCV SOFTWARE INNOSLATE ACTION DIAGRAM

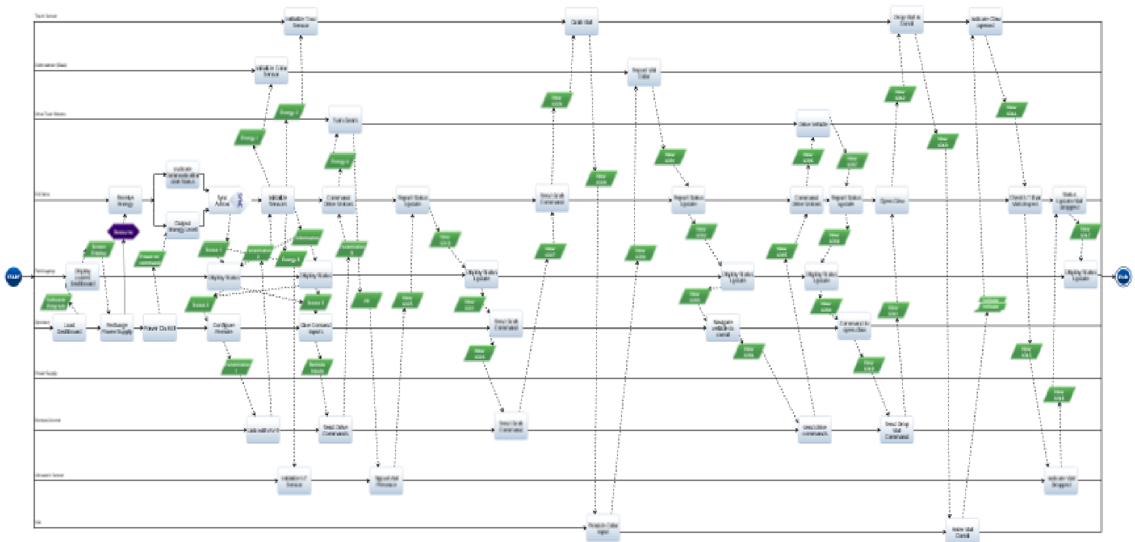

Figure 49. TVC Software Innoslate Action Diagram

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APPENDIX B: ACV SOFTWARE INNOSLATE ACTION DIAGRAM

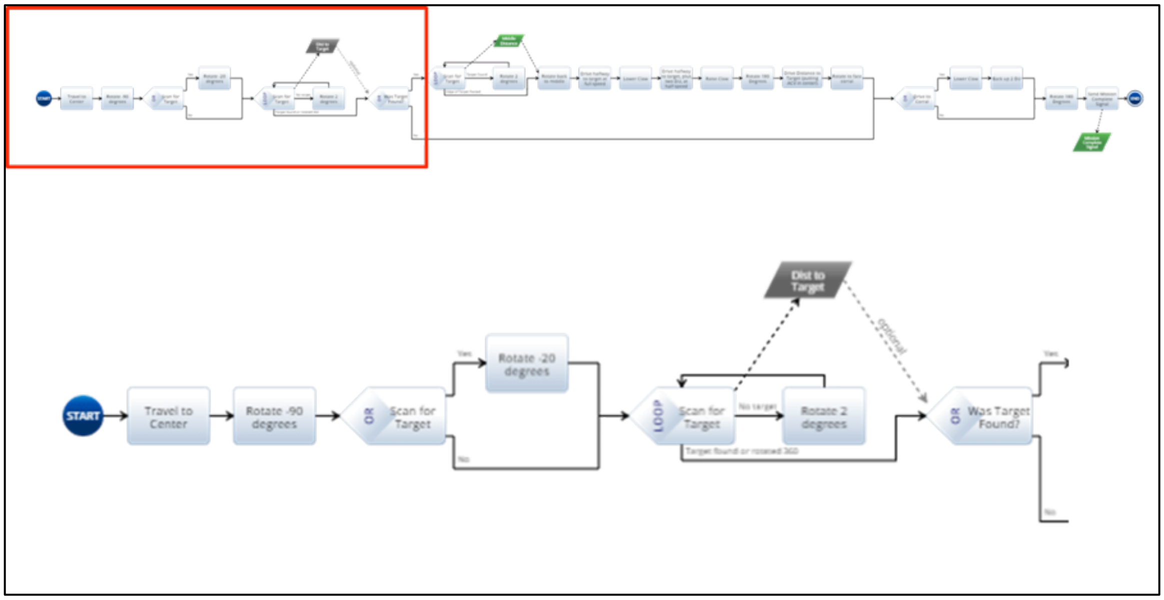

Figure 50. *FourByFour* action diagram view 1

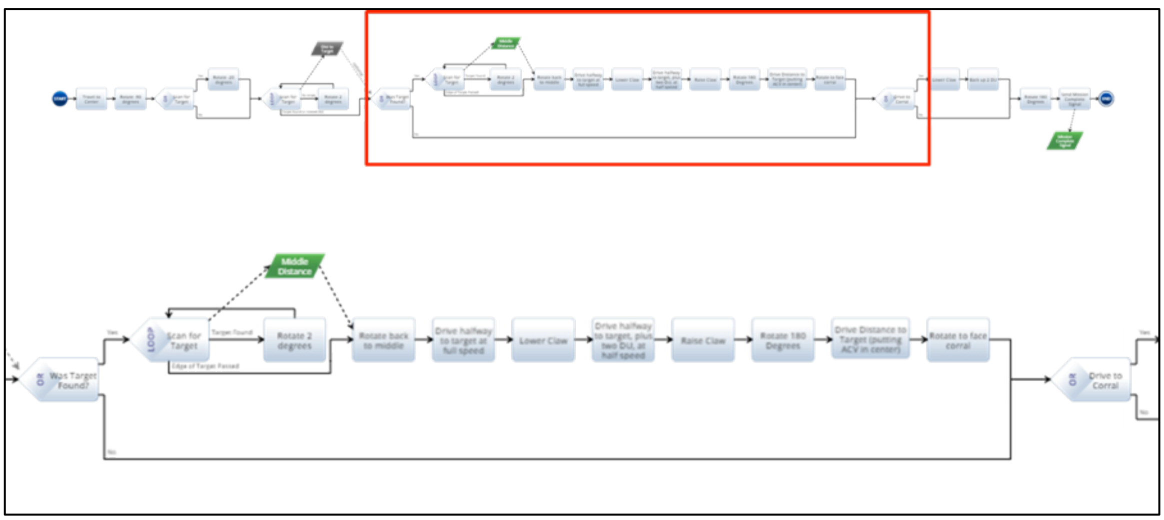

Figure 51. *FourByFour* action diagram view 2

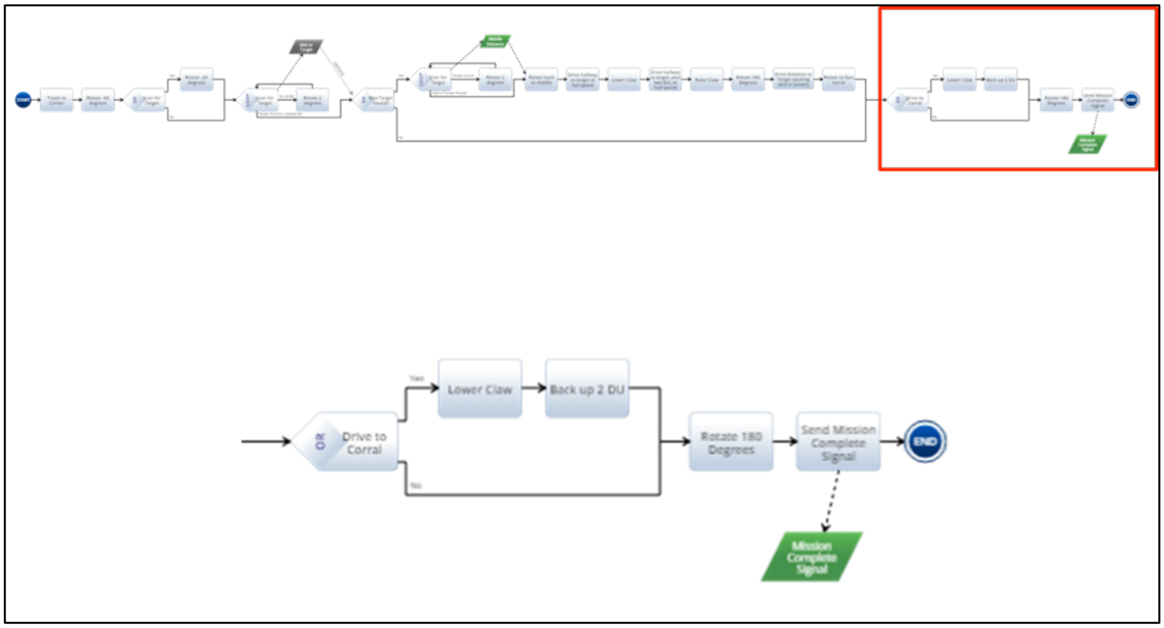

Figure 52. *FourByFour* action diagram view 3

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